ASTROPHYSICS AT THE HIGHEST ENERGY FRONTIERS

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Abstract.
I discuss recent advances being made in the physics and astrophysics of cosmic rays and cosmic γ-rays at the highest observed energies as well as the related physics and astrophysics of very high energy cosmic neutrinos. I also discuss the connections between these topics.

1. Introduction

In these lectures, I will discuss physics and astrophysics at the highest energies using current astrophysical observations. By taking a synoptic view of ultrahigh energy hadrons, photons and neutrinos, one can gain insights into the profound connections between different fields of observational astronomy and astrophysics which use different experimental techniques. Observations have been made of cosmic γ-rays up to 50 TeV energy and of ultrahigh energy cosmic rays up to 300 EeV (3×10^8 TeV). As of this date, no very high or ultrahigh energy cosmic neutrinos have been detected, however, the *AMANDA* (Antarctic Muon and Neutrino Detector Array) experiment, now in operation, is searching for neutrinos above 1 TeV energy (Wischnewski 2002).

The subjects of these lectures concern some of the deepest questions in frontiers of cutting-edge astrophysics. They also involve physics at the highest energy frontiers. The new physics which has been and may be invoked to explain the highest energy observations comprise such questions as the violation of Lorentz invariance (special relativity), grand unification of the electroweak and strong interactions, quantum gravity theory and the question of whether we live in a universe containing new large extra dimensions.

2. The Highest Energy Gamma Rays

The highest energy γ-rays observed to date were produced by the Vela pulsar and by PSR 1706-44, by supernova remnants in our galaxy and by extragalactic sources known as blazars. Blazars are a class active galaxies believed to have supermassive black holes in their nuclei which gravitationally power jets which produce massive amounts of nonthermal radiation. They are distinguished by the condition that their jets are pointed almost directly at us, producing interesting relativistic effects such as rapid time variability and Lorentz boosted radiation and also superluminal motion in many cases (Jorstad *et al.* 2001).

2.1. PULSARS

There are two theoretical models which have been proposed to account for the origin of pulsed γ-ray emission in pulsars, *viz.*, "the outer gap model", where particle acceleration occurs in the outer magnetosphere of the pulsar (Cheng, Ho and Ruderman 1986), and "the polar cap model", where particle acceleration occurs near the magnetic polar cap of the pulsar (Daugherty and Harding 1996).

In the outer gap model, in the case of the Crab pulsar, the resulting electron-positron pairs can generate TeV γ-rays through the synchrotron-self-Compton (SSC) mechanism. In SSC emission models, the source has a natural two-peaked spectral energy distribution. The lower energy peak is produced by synchrotron radiation of relativistic electrons accelerated in the source and the higher energy peak is produced by these same electrons upscattering the synchrotron component photons to TeV energies by Compton interactions. In the case of other pulsars, the low energy photons may come from curvature radiation of electrons and positrons as they follow the magentic field lines of the pulsar. This curvature radiation would then be Compton upscattered.

In the polar cap model, the strong magnetic field near the pulsar would cut off any TeV photons emitted near the surface of the pulsar *via* single-photon electron-positron pair production off the magnetic field (Erber 1966). Thus, the detection of TeV pulsed emission from ordinary pulsars would favor the outer gap model. However, for millisecond pulsars, whose B-fields are 3-4 orders of magnitude lower than is the case for regular pulsars, the high energy cutoff from single-photon pair production is 3-4 orders of magnitude higher in energy (Bulik *et al.* 2000).Thus, TeV emission may be detected in these sources in the future even in the case of the polar cap γ-ray production.

2.2. SUPERNOVA REMNANTS

Very high energy (TeV) γ-rays have been reported from several supernova remnants, *viz.*, the Crab Nebula (Weekes *et al.* 1989), the Vela pulsar wind nebula (Yoshikoshi *et al.* 1997), and the nebulae associated with PSR 1706-44 (Kifune *et al.* 1995), Cassiopeia A (Pühlhofer *et al.* 1999), SN1006 (Tanimori *et al.* 1989), and RXJ1713.7-3946 (Muraishi *et al.* 2000).

The SSC mechanism has been invoked to account for the TeV emission in the Crab Nebula (de Jager and Harding 1992).Another mechanism which has been proposed to explain the TeV emission in supernova remnants is the Compton scattering of very high energy relativistic electrons off the 2.7 K cosmic background radiation. This has been proposed for specifically for the remnant SN1006 (*e.g.*, , Pohl *et al.* 1996; Mastichiadas and de Jager 1996).

There is also the important possibility that TeV γ-rays could be produced in supernova remnants by accelerated highly relativistic *protons* interacting with interstellar gas nuclei in the vicinity of the remnant and producing very high energy γ-rays through the mechanism of the production and decay of neutral pions (π^0's) (Drury, Aharonian and Völk 1994; Gaisser, Protheroe and Stanev 1998). Almost 70 years ago, Baade and Zwicky (1934) first proposed that supernovae could provide the energy for accelerating cosmic rays in our galaxy. This hypothesis gained observational support two decades later when Shklovskii (1953) proposed that relativistic electrons radiating in the magnetic field of the Crab Nebula produced its optical continuum radiation. Indirect support for proton acceleration in supernovae came from γ-ray observations in the 1970s (Stecker 1975; 1976). It now appears that evidence for the hadronic π^0 production mechanism may have been found for the source RXJ1713.7-3946 (Enomoto *et al.* 2002). While the evidence is not definitive (Butt *et al.* 2002), we can hope for a resolution with future observations. The detection of high energy neutrinos from RXJ1713.7-3946 would serve as a smoking gun for hadronic producion since these neutrinos would be produced by the decay of $\pi^{\pm}$ mesons (Alvarez-Mũniz and Halzen 2002).

2.3. BLAZARS

Blazars were first discovered as the dominant class of extragalactic high energy γ-ray sources by the *EGRET* detector on the Compton Gamma Ray Observatory (*CGRO*). Because they are at large extragalactic distances, their spectra are predicted to be modified by strongly redshift dependent absorption effects caused by interactions of these γ-rays with photons of the intergalactic IR-UV background radiation (Stecker, de Jager and Salamon 1992).

The highest energy extragalactic γ-ray sources are those blazars known as X-ray selected BL Lac objects (XBLs), or alternatively as high frequency BL Lac objects (HBLs). They are expected to emit photons in the multi-TeV energy range (Stecker, de Jager and Salamon 1996), but only the nearest ones are expected to be observable, the others being hidden by intergalactic absorption (Stecker *et al.* 1992).

There are now $\sim$70 "grazars" (γ-ray blazars) which have been detected by the *EGRET* team at GeV energies (Hartman *et al.* 1999) These sources, optically violent variable quasars and BL Lac objects, have been detected out to a redshift of $\sim$2.3.

In addition, several TeV grazars have been discovered at low redshifts ($z < 0.13$), *viz.*, Mkn 421 at $z = 0.031$ (Punch *et al.* 1992), Mkn 501 at $z = 0.034$ (Quinn *et al.* (1996),1ES2344+514 at $z = 0.44$ (Catanese *et al.* 1998), PKS 2155-304 at $z = 0.117$ (Chadwick *et al.* 1998), and 1ES1426+428 (a.k.a. H1426+428) at $z = 0.129$ (Aharonian *et al.* 2002; Horan *et al.* 2002). These sources all fit the two candidate source criteria of Stecker *et al.* (1996) of closeness and a high frequency synchrotron peak which is prominant in X-ray emission. Recently, another criterion has been suggested for TeV candidate sources, *viz.* a relatively large flux in the synchrotron peak (Costamante and Ghisellini 2001). The closeness criterion has to do with extragalactic TeV γ-ray absorption by pair production (Stecker *et al.* 1992). The other two criteria have to do with the synchrotron-self-Compton (SSC) mechanism believed to be primarily responsible for the TeV emission of the HBL sources. In the SSC models, an HBL blazar has a two-peaked spectral energy distribution (see pulsar section above) with the lower energy peak in the radio to X-ray range and the higher energy peak in the X-ray to multi-TeV γ-ray range.

Very high energy γ-ray beams from blazars can be used to measure the intergalactic infrared radiation field, since pair-production interactions of γ-rays with intergalactic IR photons will attenuate the high-energy ends of blazar spectra (Stecker *et al.* 1992). In recent years, this concept has been used successfully to place upper limits on the the diffuse infrared radiation background (DIRB) (Stecker and de Jager 1993, 1997; Dwek 1994; Stanev and Franceschini 1997; Biller *et al.* 1998). Determining the DIRB, in turn, allows us to model the evolution of the galaxies which produce it. As energy thresholds are lowered in both existing and planned ground-based air Čerenkov light detectors and with the launch of the *GLAST* (Gamma-Ray Large Area Space Telescope) in 2006, cutoffs in the γ-ray spectra of more distant blazars are expected, owing to extinction by the DIRB. These can be used to explore the redshift dependence of the DIRB (Salamon and Stecker 1998 (SS98)).

2.4. THE DIFFUSE LOW ENERGY PHOTON BACKGROUND AND EXTRAGALACTIC GAMMA RAY ABSORPTION

The formulae relevant to absorption calculations involving pair-production interactions with redshift factors are given in Stecker *et al.* (1992). For γ-rays in the TeV energy range, the pair-production cross section is maximized when the soft photon energy is in the infrared range:

$$\lambda(E_\gamma) \simeq \lambda_e \frac{E_\gamma}{2m_e c^2} = 1.24 E_{\gamma,TeV} \ \ \mu m \tag{1}$$

where $\lambda_e = h/(m_e c)$ is the Compton wavelength of the electron. For a 1 TeV γ-ray, this corresponds to a soft photon having a wavelength ~ 1 μm. (Pair-production interactions actually take place with photons over a range of wavelengths around the optimal value as determined by the energy dependence of the cross section.) If the emission spectrum of an extragalactic source extends beyond 20 TeV, then the extragalactic infrared field should cut off the *observed* spectrum between $\sim$ 20 GeV and $\sim$ 20 TeV, depending on the redshift of the source (Stecker and Salamon 1997; SS98).

Several attempts have been made to infer the IR SED (spectral energy distribution) of the DIRB either from model calculations or observations. (See Hauser and Dwek (2001) for the latest review.) Such information can be used to calculate the optical depth for TeV range photons as a function of energy and redshift. Figure 1 summarizes the observationally derived values for the extragalactic optical-UV, near-IR and far-IR fluxes which now exist. We will refer to the totality of these fluxes as the extragalactic background light (EBL) Unfortunately, foreground emission prevents the direct detection of the EBL in the mid-IR wavelength range. (See discussion in Hauser and Dwek 2001.) However, other theoretical models such as those of Tan, Silk and Balland (1999), Rowan-Robinson (2000) and Xu (2000) predict fairly flat SEDs in the mid-infrared range with average flux levels in the 3 to 4 nW m^{-2}sr $^{-1}$ as do the Malkan and Stecker (2001) models shown in Figure 1. These flux levels are also sconsistent with the indirect mid-IR constraints indicated by the box in Figure 1. (These constraints are summarized by Stecker (2001).) [1]

The two Malkan and Stecker (2001) SED curves for the DIRB, extended into the optical-UV range by the hybrid model of de Jager and Stecker (2002) (DS02), give a reasonable representation of the EBL in the UV to

[1]We note that the *COBE-DIRBE* group has argued that a real flux derived from the *COBE-DIRBE* data at 100 μm, as claimed by Lagache *et al.* (2000), is untenable because isotropy in the residuals (after foreground subtractions) could not be proven. Dwek *et al.* (1998) have concluded that only a conservative lower limit of 5 m^{-2}sr^{-1} could be inferred at 100 μm.

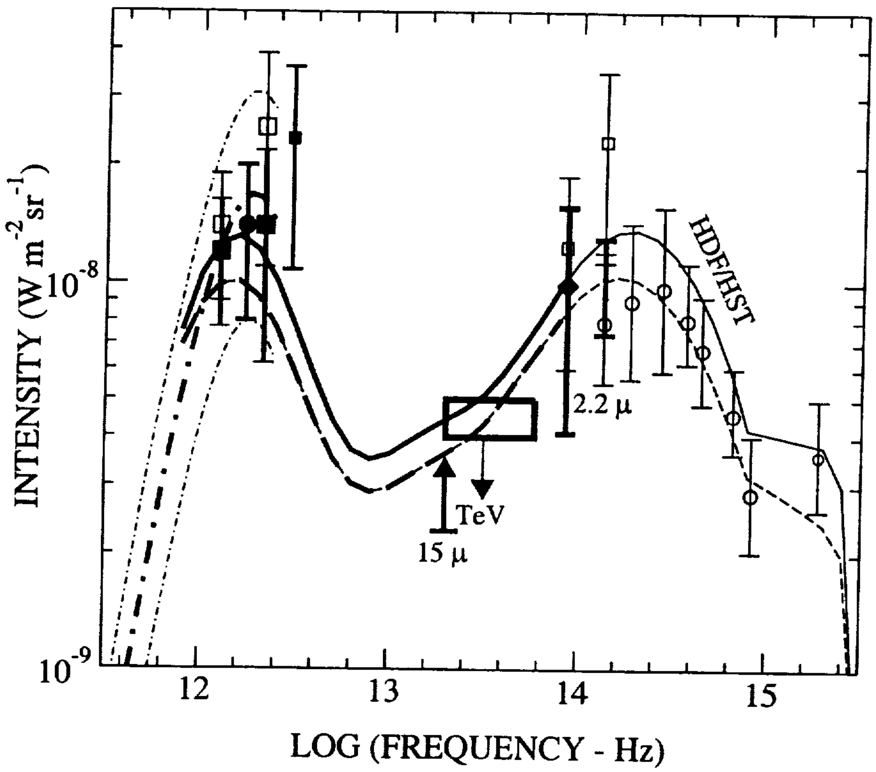

Figure 1. The SED of the EBL (see text for references and descriptions). All error bars given at the $\pm 2\sigma$ level. The Malkan and Stecker (2001) fast evolution model is shown by the upper, thick solid curve between $\log_{10} \nu = 11.8$ to 13.8) and their baseline model is shown by the thick dashed line over the same frequency range. Convergent Hubble Deep Field galaxy counts (Madau and Pozzetti 2001): open circles; Ground-based galaxy counts limits at 2.2μm (see text): thick vertical bar marked "2.2μ"; *COBE-DIRBE* photometric sky residuals (Wright and Reese 2000): small open squares; TeV γ-ray-based upper limits: thick box marked "TeV" (see text for references); *ISOCAM* lower limit at 15μm: upward arrow marked 15μ (Elbaz *et al.* 1999); *COBE-DIRBE* far-IR sky residuals (Hauser *et al.* 1998): large open squares at 140 μm and 240 μm; *COBE-DIRBE* data recalibrated using the *COBE- FIRAS* calibration (see text): large solid squares without error bars; *ISOCAM* 170 μm flux (Kiss *et al.* 2001): solid circle; *COBE-FIRAS* far-IR sky residuals (Fixsen, *et al.* 1998): thick dot-dash curve with $\sim$ 95% confidence band (thin dot–dash band); 100μm *COBE-DIRBE* point (Lagache *et al.* 2000): small solid square; flux at 3.5 μm from *COBE-DIRBE* (Dwek and Arendt 1998): solid diamond.

far-IR. Other EBL models in the literature whose flux levels roughly fit the present data and have the same spectral characteristics, *i.e.*, a stellar optical peak, a far-IR dust emission peak, and a mid-IR valley which allows for some warm dust emission (see review of Hauser and Dwek 2001), should give similar results on the optical depth of the near Universe $\tau(E, z)$ to high

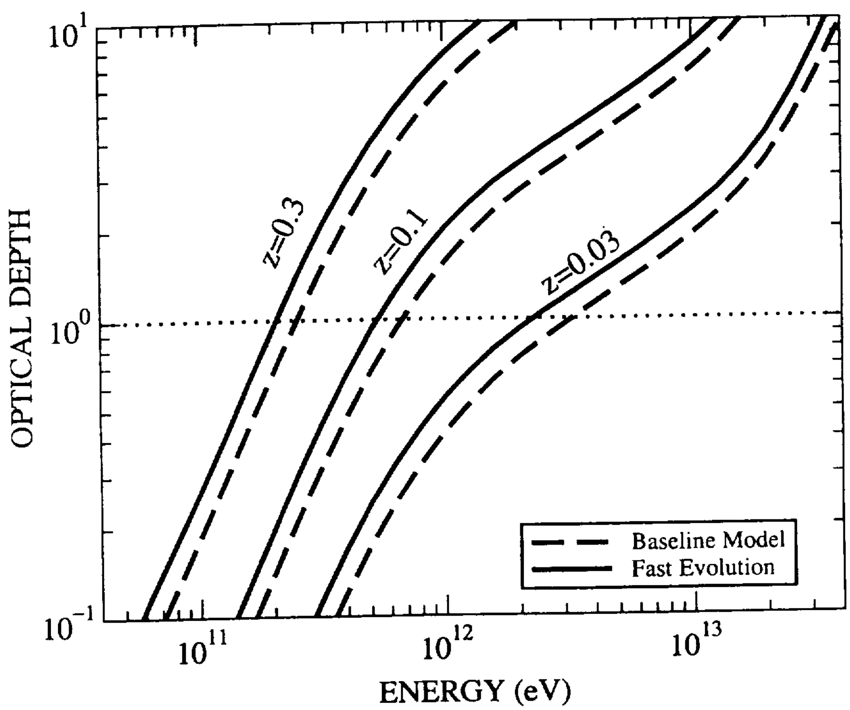

Figure 2. The optical depth for γ-rays above 50 GeV given for redshifts between 0.03 and 0.3 (as labelled) calculated using the medium (dashed lines) and fast evolution (solid lines) SED of Malkan and Stecker (2001).

energy γ-rays.

DS02 rederived the optical depth of the universe to high energy γ-rays as a function of energy and redshift for energies betweeen 50 GeV and 100 TeV and redshifts between 0.03 and 0.3 using their derived hybrid EBL SEDs. Figure 2 shows $\tau(E, z)$ calculated using the baseline and fast evolution hybrid models of DS02 for γ-ray energies down to $\sim$ 50 GeV, which is the approximate threshold energy for meaningful image analyses in next generation ground based γ-ray telescopes such as *MAGIC, H.E.S.S.* and *VERITAS.* Where they overlap, the DS02 results are in good agreement with the metallicity corrected results of SS98,which give the optical depth of the universe to γ-rays out to a redshift of 3 and extend to lower energies (See Section 2.7.)

DS02 also obtained parametric expressions for $\tau(E, z)$ for $z < 0.3$ and $0.1 < E_{\rm TeV} < 50$ which are accurate to within 5% and can be used for numerical calculations.

2.5. THE NEARBY TEV BLAZAR SOURCE MKN 501

The nearby blazar Mkn 501 is of particular interest because a very detailed determination of its spectrum was obtained by observing it while it was strongly flaring in 1997. The spectrum observed at that time by the *HEGRA* air Čerenkov telescope system (Aharonian, *et al.* 2001a) extended to energies greater than 20 TeV, the highest energies yet observed from an extragalactic source.

Using this observational data, DS02 derived the *intrinsic* γ-ray spectrum of Mkn 501 during its 1997 flaring state by compensating for the effect of intergalactic absorption. They found that the time averaged spectral energy distribution of Mkn 501 while flaring had a broad, flat peak in the $\sim$5–10 TeV range which corresponds to the broad, flat time averaged X-ray peak in the ~ 50–100 keV range observed during the flare. The spectral index of the derived intrinsic differential photon spectrum for Mkn 501 at energies below $\sim$2 TeV was found to be $\sim$1.6–1.7. This corresponds to a time averaged spectral index of 1.76 found in soft X-rays at energies below the X-ray (synchrotron) peak (Petry *et al.* 2000). These results appear to favor an SSC origin for the TeV emission together with jet parameters which are consistent with time variability constraints within the context of a simple SSC model. The similarity of the soft X-ray and $\sim$TeV spectral indices of the two components of the source spectrum implies that γ-rays below ~ 1 TeV are produced in the Thomson regime by scattering off synchrotron photons with energies in the optical-IR range. On the other hand, γ-rays near the $\sim 7 \pm 2$ TeV Compton peak appear to be the result of scattering in the Klein-Nishina range.

The observed spectrum between 0.56 and 21 TeV was obtained from contemporaneous observations of Mkn 501 by the *HEGRA* group (Aharonian *et al.* 2001a) and the *Whipple* group (Krennrich *et al.* 1999). These observations are consistent with each other (within errors) in the overlapping energy range between 0.5 and 10 TeV, resulting in a single spectrum extending over two decades of energy, marked "OBSERVED" in Figure 3.

Using both the *Whipple* and *HEGRA* data and correcting for absorption by multiplying by $e^{\tau(E)}$ evaluated at $z = 0.034$ with their newly derived values for the opacity, DS02 derived the intrinsic spectrum of Mkn 501 over two decades of energy. This is given by the data points and two curves marked "INTRINSIC" in Figure 3. The upper of these curves corresponds to the fast evolution case; the lower curve corresponds to the baseline model case.

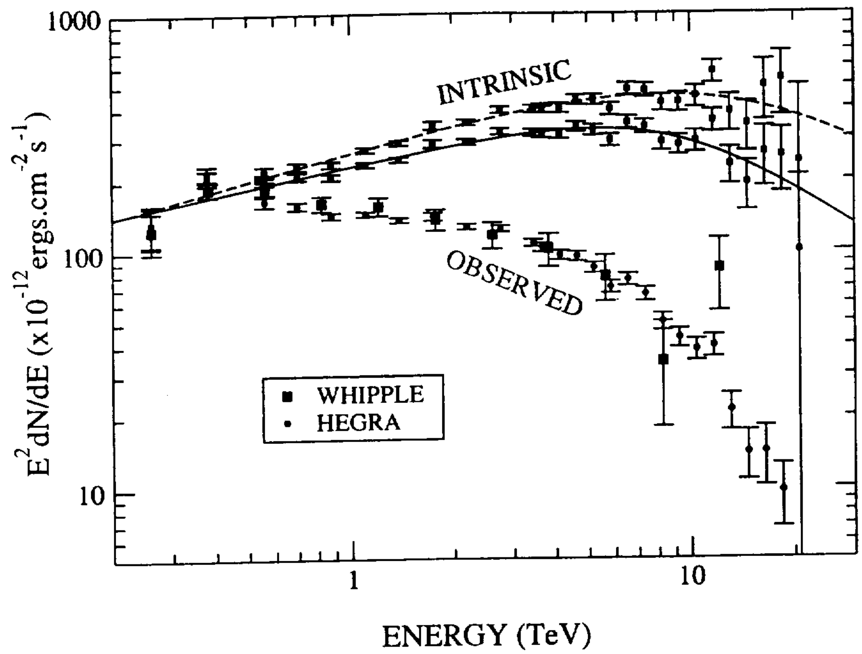

Figure 3. The observed spectrum and derived intrinsic spectrum of Mkn 501. The observed spectral data are as measured by *HEGRA* (solid circles) and *Whipple* (solid squares). The upper points are the absorption corrected data points (marked "INTRINSIC") using our fast evolution hybrid EBL (upper data set and solid curve fit) and baseline hybrid EBL (lower data set with dashed curve fit).

Fossati *et al.* (2000) has suggested a parameterization to describe smoothly curving blazar spectra. This parameterization is of the form

$$\frac{dN}{dE} = KE^{-\Gamma_1}\left(1 + (\frac{E}{E_B})^f\right)^{(\Gamma_1-\Gamma_2)/f} \tag{2}$$

A spectrum of this form changes gradually from a spectral index of Γ_1 to an index of Γ_2 when the energy E increases through the break energy E_B. The parameter f describes the rapidity ("fastness") of the change in spectral index over energy. DS02 applied the formalism of Fossati *et al.* (2000) to their Mkn 501 intrinsic flare spectrum and found best-fits for the parameters K, E_B, f, Γ_1 and Γ_2 after correcting the observed spectrum for intergalactic absorption.

Whereas the low energy spectral index Γ_1 was found to be well constrained, the higher energy index Γ_2 is unconstrained. The SED peaks at $E_M \sim 8-9$ TeV (independent of the unconstrained Γ_2) in the case where the fast evolution EBL is assumed and that $E_M \sim 5$ TeV if the baseline EBL is assumed. (See Figure 3)

Since Mkn 501 is a giant elliptical galaxy with little dust, it is reasonable to assume that the galaxy itself does not produce enough infrared radiation to provide a significant opacity to high energy γ-rays. Such BL Lac objects have little gas (and therefore most likely little dust) in their nuclear regions. It also appears that γ-ray emission in blazars takes place at superluminal knots in the jet downstream of the core and at any putative accretion disk. So, if the EBL SED of DS02 is approximately correct, it is reasonable to assume that the dominant absorption process is intergalactic and that pair-production in the jet in negligible. This hypothesis is supported by the fact that the high energy γ-ray SED did not steepen during the flare. This implies that the optical depth given by eq. (4) is less than unity out to the highest observed energy $E \sim 20$ TeV. Thus, it appears that the high energy turnover in the observed Mkn 501 γ-ray spectrum above ~ 10 TeV can be understood solely as a result of intergalactic absorption.

The intrinsic SED of Mkn 501 derived by DS02 is quite flat in the multi-TeV range as shown in Figure 3. This is in marked contrast to the dramatic turnover in its observed SED. This is strong evidence that the observed spectrum shows just the absorption effect predicted. We will see that the spectral observations of other blazars, although not nearly as good in most cases, also exhibit evidence of intergalactic absorption.

2.6. ABSORPTION IN THE SPECTRA OF OTHER BLAZARS

Observations of Mkn 421, the closest TeV blazar which has a redshift very similar to that of Mkn 501, were made by the *Whipple* group up to an energy of 17 TeV (Krennrich *et al.* 2002). Their results indicate a turnover in the spectrum at energies above ~4 TeV caused by extragalactic absorption, quite similar to that observed in the spectrum of Mkn 501 (see above).

As to sources at somewhat higher redshifts, Stecker (1999) considered the blazar source PKS 2155-304, located at a moderate redshift of 0.117, which has been reported by the Durham group to have a flux above 0.3 TeV of $\sim 4 \times 10^{-11}$ cm^{-2} s^{-1}, close to that predicted by a simple SSC model.Using absorption results obtained by Stecker and de Jager (1998) and assuming an E^{-2} source spectrum, Stecker (1999) predicted an absorbed (observed) spectrum as shown in Figure 4. As indicated in the figure, it was predicted that this source should have its spectrum steepened by ~ 1 in its spectral index between ~ 0.3 and ~ 3 TeV and should show a pronounced absorption turnover above ~ 6 TeV.

There are now recent observations of the spectrum of another TeV blazar 1ES1426+428 at a redshift of 0.129, not too different from that

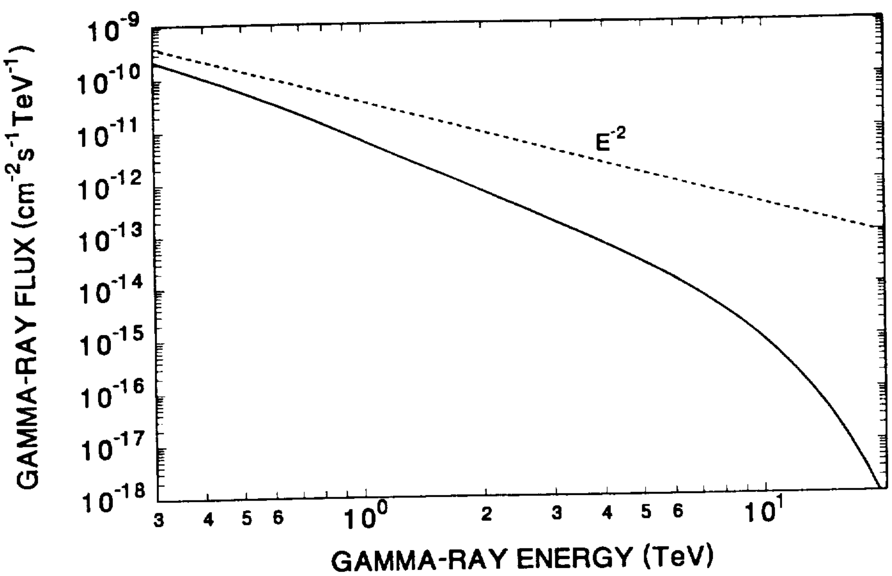

Figure 4. Predicted differential absorbed spectrum, for PKS 2155-304 (solid line) assuming an E^{-2} differential source spectrum (dashed line) normalized to the integral flux given by Chadwick *et al.* (1998).

of PKS 2155-304. Interestingly, it has been found by three groups that the spectrum of this source is quite steep, with a photon differential spectral index greater than 3 (Aharonian *et al.* 2002; Petry *et al.* 2002; Djannati-Atai, *et al.* 2002). This steep spectrum, similar to that predicted by Stecker (1999) for PKS2155-304 at a redshift of 0.117, is more evidence for extragalactic absorption.

2.7. THE GAMMA-RAY OPACITY AT HIGH REDSHIFTS

Salamon and Stecker (1998) (SS98) have calculated the γ-ray opacity as a function of both energy and redshift for redshifts as high as 3 by taking account of the evolution of both the SED and emissivity of galaxies with redshift. In order to accomplish this, they adopted the recent analysis of Fall *et al.* (1996) and also included the effects of metallicity evolution on galactic SEDs. They then gave predicted γ-ray spectra for selected blazars and extend our calculations of the extragalactic γ-ray background from blazars to an energy of 500 GeV with absorption effects included. Their results indicate that the extragalactic γ-ray background spectrum from blazars should steepen significantly above 15-20 GeV, owing to extragalactic absorption. Future observations of such a steepening would thus provide a test of the blazar origin hypothesis for the γ-ray background radiation.

SS98 calculated stellar emissivity as a function of redshift at 0.28 μm, 0.44 μm, and 1.00 μm, both with and without a metallicity correction. Their results agree well with the emissivity obtained by the Canada-France Redshift Survey (Lilly *et al.* 1996)over the redshift range of the observations ($z \leq 1$). The stellar emissivity in the universe is found to peak at $1 \leq z \leq 2$, dropping off steeply at lower reshifts and is roughly constant higher redshifts (*e.g.*, Steidel 1999). Indeed, Madau and Schull (1996) have used observational data from the Hubble Deep Field to show that metal production has a similar redshift distribution, such production being a direct measure of the star formation rate. (See also Pettini *et al.* 1994.)

The optical depth of the universe to γ-rays as a function of energy at various redshifts out to $z = 3$ which was derived by SS98 is shown in Figure 5.

2.8. THE EFFECT OF ABSORPTION ON THE SPECTRA OF BLAZARS AND THE GAMMA-RAY BACKGROUND

With the γ-ray opacity $\tau(E_0, z)$ calculated out to $z = 3$ (see previous section), the cutoffs in blazar γ-ray spectra caused by extragalactic pair production interactions with stellar photons can be predicted. The left graph in Figure 6 from SS98 shows the effect of the intergalactic radiation background on a few of the grazars observed by *EGRET*, *viz.*, 1633+382, 3C279, 3C273, and Mkn 421, assuming that the mean spectral indices obtained for these sources by *EGRET* extrapolate out to higher energies attenuated only by intergalactic absorption. In considering this figure, it should be noted that observed cutoffs in many grazar spectra may also be affected by natural cutoffs in their source spectra (Stecker, de Jager and Salamon 1996) and intrinsic absorption may also be important in some sources (Protheroe and Biermann 1996).

Figure 7 shows the background spectrum predicted from unresolved blazars (Stecker and Salamon 1996a; SS98),compared with the *EGRET* data (Sreekumar *et al.* 1998). Note that the predicted spectrum steepens above 20 GeV, owing to extragalactic absorption by pair-production interactions with radiation from external galaxies, particularly at high redshifts.

Again we note that the predicted background above 10 GeV from unresolved blazars is uncertain because many blazars are expected to have intrinsic cutoffs in their γ-ray production spectra and by intrinsic γ-ray absorption within such sources is also a possibility. Thus, above 10 GeV the

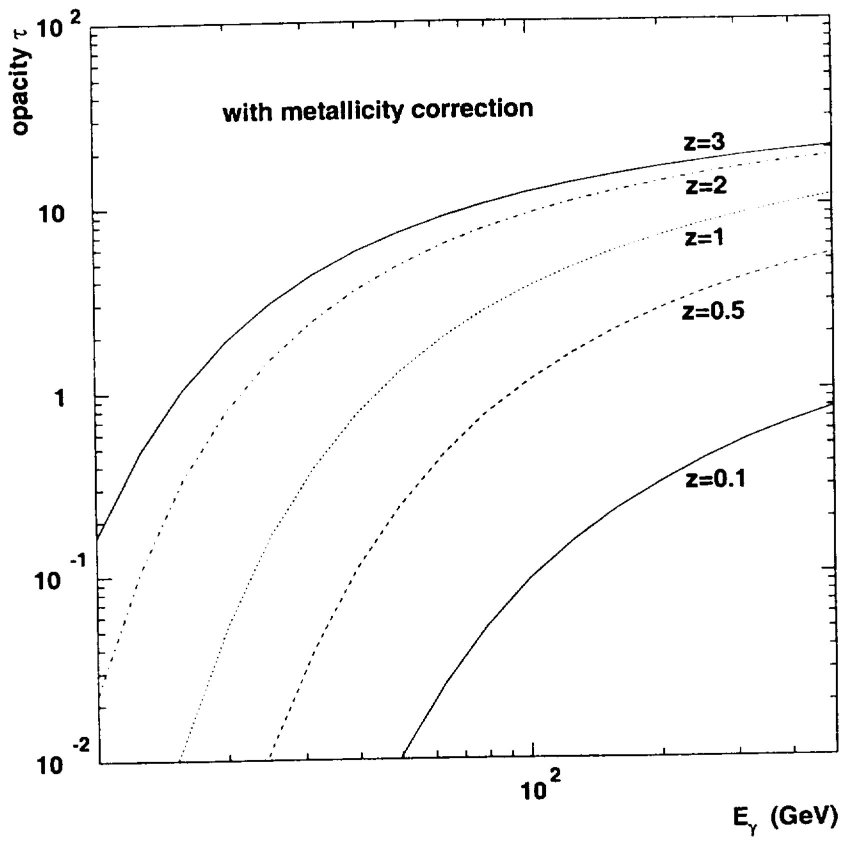

Figure 5. The optical depth for γ-rays as a function of energy for various redshifts calculated using the metallicity correction of SS98.

calculated background flux from unresolved blazars shown in Figure 7 may actually be an upper limit. Whether cutoffs in grazar spectra are primarily caused by intergalactic absorption can be determined by observing whether the grazar cutoff energies have the type of redshift dependence predicted here.

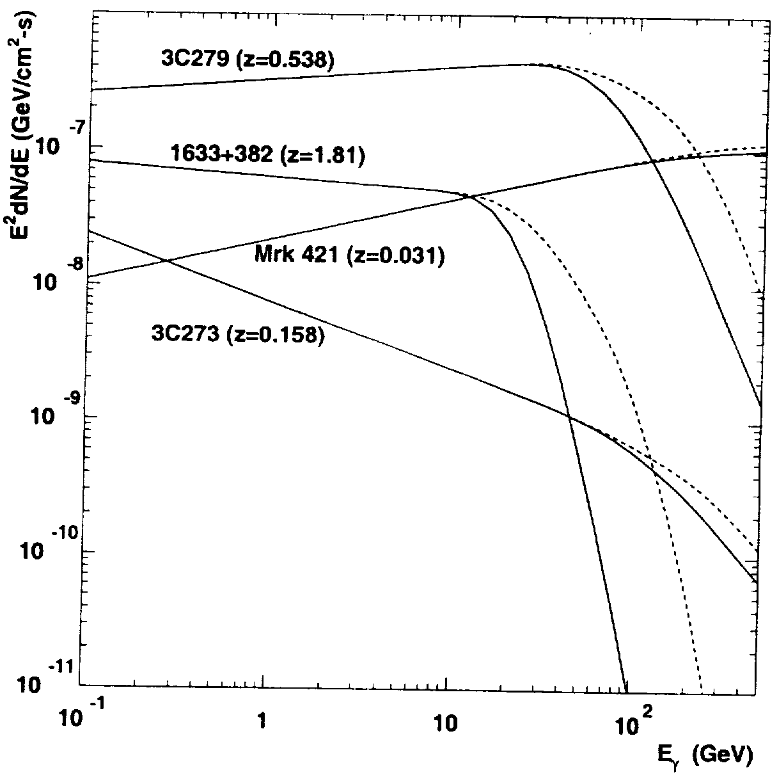

Figure 6. The effect of intergalactic absorption by pair-production on the power-law spectra of four prominent grazars: 1633+382 (z = 1.81), 3C279 (z = 0.54), 3C273 (z = 0.15), and Mkn 421 (z = 0.031) assuming an extrapolation of the spectral indeces for these sources measured by *EGRET* to high energy.

2.9. CONSTAINTS ON THE REDSHIFTS OF GAMMA-RAY BURSTS

The results of the SS98 absorption calculations can also be used to place limits on the redshifts (or distances) of γ-ray bursts. On 17 February 1994, the *EGRET* telescope observed a γ-ray burst which contained a photon of energy $\sim$ 20 GeV (Hurley *et al.* 1994). If one adopts the opacity results

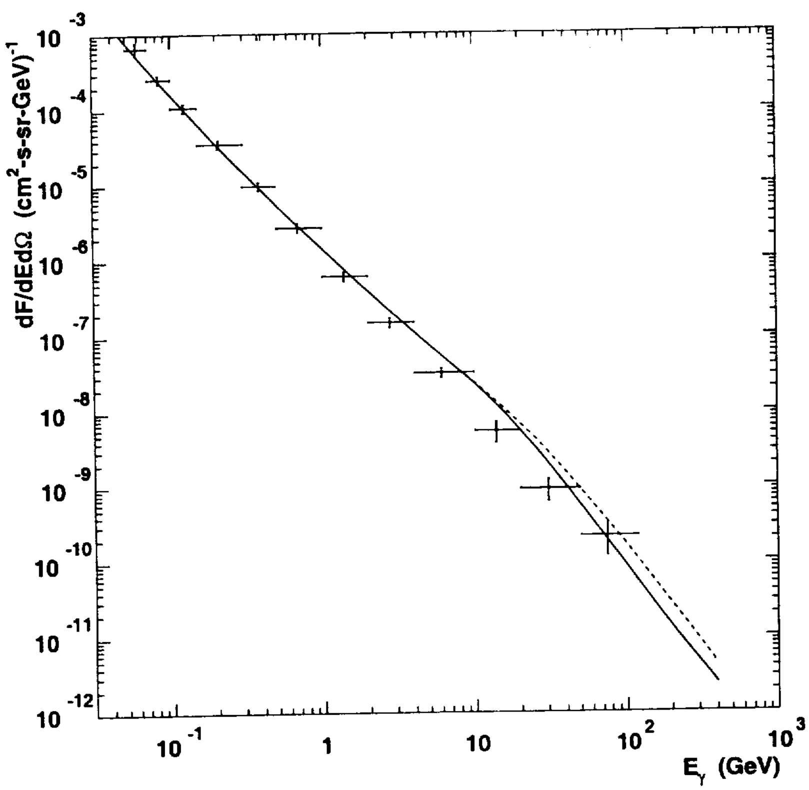

Figure 7. The extragalactic γ-ray background spectrum predicted by the unresolved blazar model of Stecker and Salamon (1996) with absorption included, calculated for a mean *EGRET* point-source sensitivity of 10^{-7} cm^{-2}s^{-1}, compared with the *EGRET* data on the γ-ray background (Sreekumar *et al.* 1998). The solid (dashed) curves are calculated with (without) the metallicity correction function (from SS98).

which include the metallicity correction, the highest energy photon in this burst would be constrained probably to have originated at a redshift less than $\sim$2.

On 17 April 1997, the ground based "Milagrito detector" observed the burst GRB970417a with an effective threshold of energy of 0.65 TeV (Atkins *et al.* 2002).Using the opacity curves derived by DS02 as shown in Figure 2, we can obtain constraints on the maximum redshift of this GRB. Since the observed burst contained photons of energies down to 0.65 TeV, the maximum redshift of GRB970417a was $z_{max} \simeq 0.1$.

Future detectors such as *GLAST* (Bloom 1996)should be able to place redshift constraints on bursts observed at higher energies. Such constraints may further help to identify the host galaxies of γ-ray bursts.

2.10. CONSTRAINTS ON THE VIOLATION OF LORENTZ INVARIANCE.

Lorentz invariance violation can be described quite simply in terms of different maximal attainable velocities of different particle species as measured in the preferred frame (Coleman and Glashow 1999). Following the well-defined formalism for LI violation discussed by Coleman and Glashow (1999), (see also Colladay and Kostelecky 1998), the maximum attainable velocity of an electron need not equal the *in vacua* velocity of light, *i.e.*, $c_e \neq c_\gamma$. The physical consequences of this violation of LI depend on the sign of the difference. Defining

$$c_e \equiv c_\gamma(1+\delta)\ , \qquad 0 < |\delta| \ll 1\ , \tag{3}$$

Stecker and Glashow (2001) consider the two cases of positive and negative values of δ separately.

Case I: If $c_e < c_\gamma$ ($\delta < 0$), the decay of a photon into an electron-positron pair is kinematically allowed for photons with energies exceeding

$$E_{\rm max} = m_e\,\sqrt{2/|\delta|}\ . \tag{4}$$

The decay would take place rapidly, so that photons with energies exceeding $E_{\rm max}$ could not be observed either in the laboratory or as cosmic rays. From the fact that photons have been observed with energies $E_\gamma \geq 50$ TeV from the Crab nebula (Tanimori *et al.* 1998),it follows from eq.(9) that $E_{\rm max} \geq 50$ TeV, or that $-\delta < 2 \times 10^{-16}$.

Case II: Here we are concerned with the remaining possibility, where $c_e > c_\gamma$ ($\delta > 0$) and electrons become superluminal if their energies exceed $E_{\rm max}/2$. Electrons traveling faster than light will emit light at all frequencies by a process of 'vacuum Čerenkov radiation.' This process occurs rapidly, so that superluminal electron energies quickly approach $E_{\rm max}/2$. However, because electrons have been seen in the cosmic radiation with energies up to ~ 1 TeV (Nishimora *et al.* 1980),it follows that $E_{\rm max} \geq 2$ TeV, which leads to an upper limit on δ for this case of 1.3×10^{-13}. This limit is three orders of magnitude weaker than the limit obtained for Case I. However, if the observed $\sim$TeV γ-ray emission from the Crab Nebula is produced by very high energy electrons *via* the SSC mechanism (de Jager and Harding

1992), then the implied maximum electron energy is $\sim 10^4$ TeV. In this case we would get an *indirect* upper limit on δ of 1.3×10^{-21}.

Stecker and Glashow (2001) have also shown how stronger bounds on δ can be set using observations of very high energy cosmic ray photons. For case I, the discussion is trivial: The mere detection of cosmic γ-rays with energies greater that 50 TeV from sources within our galaxy would improve the bound on δ. The situation for case II is more interesting.

If LI is broken so that $c_e > c_\gamma$, the threshold energy for the pair production process $\gamma + \gamma \rightarrow e^+ + e^-$ is altered because the square of the four-momentum becomes

$$2\epsilon E_\gamma(1 - \cos\theta) - 2E_\gamma^2\delta = 4\gamma^2 m_e^2 > 4m_e^2 \tag{5}$$

where ϵ is the energy of the low energy (infrared) photon and θ is the angle between the two photons. The second term on the left-hand-side comes from the fact that $c_\gamma = \partial E_\gamma/\partial p_\gamma$.

For head-on collisions ($\cos\theta = -1$) the minimum low energy photon energy for pair production becomes

$$\epsilon_{min} = m_e^2/E_\gamma + (E_\gamma\delta)/2 \tag{6}$$

It follows that the condition for a significant increase in the energy threshold for pair production is

$$E_\gamma \geq E_{\max} \qquad \text{or equivalently} \qquad \delta \geq 2m_e^2/E_\gamma^2. \tag{7}$$

Extragalactic photons with the highest energies yet observed originated in a powerful flare coming from Mkn 501 (Aharonian *et al.* (1999).We have seen that the Mkn 501 observations indicate that its multi-TeV spectrum is consistent with what one would expect from intergalactic absorption (SD02).Since there is no significant decrease in the optical depth of the universe at the distance of Mkn 501 for $E_\gamma \leq 20$ TeV, it then follows from eq. (5) that $\delta \leq 2(m_e/E_\gamma)^2 = 1.3 \times 10^{-15}$. This constraint is two orders of magnitude stronger than that obtained from cosmic-ray electron data (see above) for the case when $\delta > 0$ (Case II).

Further tests of LI could emerge from future observations. The detection of galactic γ-rays with energies greater than 50 TeV would strengthen the bound on δ for Case I. As for Case II, the detection of cosmic γ-rays above $100(1 + z_s)^{-2}$ TeV from an extragalactic source at a redshift z_s, would be strong evidence for LI breaking with $\delta \geq 0$. This is because the very large density (~ 400 cm^{-3}) of 3K cosmic microwave photons would otherwise absorb γ-rays of energy ≥ 100 TeV within a distance of ~ 10 kpc, with this critical energy reduced by a factor of $\sim (1 + z_s)^2$ for sources at redshift z_s (Stecker 1969).

The constraints on δ lead to constraints on quantum gravity theory. Amelino-Camelia *et al.* (1998) and Ellis *et al.* (1998) have proposed that the back reaction of the vacuum in their quantum gravity scenario would lower the effective velocity of the electron so that

$$\delta \simeq -E/M_{QG} + \text{higher order terms.} \tag{8}$$

However, as discussed above, Stecker and Glashow (2001) have shown that

$$-\delta \leq 2\times 10^{-16} \text{ for } E = 5\times 10^{4} \text{ GeV}, \tag{9}$$

since 50 TeV γ-rays have been detected from the Crab Nebula. According to eq. (8), this implies that

$$M_{QG} \simeq -E/\delta \geq 20 M_{Planck}, \tag{10}$$

where $M_{Planck} = 1.2\times 10^{19}$ GeV, is the Planck mass. Since M_{QG} is usually identified with M_{Planck} this may imply an inconsistency in this scenario.

3. The Highest Energy Cosmic Rays

3.1. THE DATA

Figure 8 shows the data (as of this writing) on the ultrahigh energy cosmic ray spectrum from the *Fly's Eye*, *AGASA* and *HiRes* detectors.[2] Other data from Havera Park and Yakutsk may be found in the review by Nagano and Watson (2000) are consistent with Figure 8. The new *HiRes* data are from Abu-Zayyad *et al.* (2002).

For air showers produced by primaries of energies in the 1 to 3 EeV range, Hayashida, *et al.* (1999) have found a marked directional anisotropy with a 4.5σ excess from the galactic center region, a 3.9σ excess from the Cygnus region of the galaxy, and a 4.0σ deficit from the galactic anticenter region. This is strong evidence that EeV cosmic rays are of galactic origin. A galactic plane enhancement in EeV events was also reported by the Fly's Eye group (Dai *et al.* 1999).

As shown in Figure 9 , at EeV energies, the primary particles appear to have a mixed or heavy composition, trending toward a light composition in the higher energy range around 30 EeV (Bird, *et al.* 1993; Abu-Zayyad, *et al.* 2000). This trend, together with evidence of a flattening in the cosmic ray spectrum on the 3 to 10 EeV energy range (Bird, *et al.* 1994; Takeda *et*

[2]The AGASA data have been reanalysed and the number of events determined to be above 100 EeV has been lowered to eight. (Teshima, private communication.)

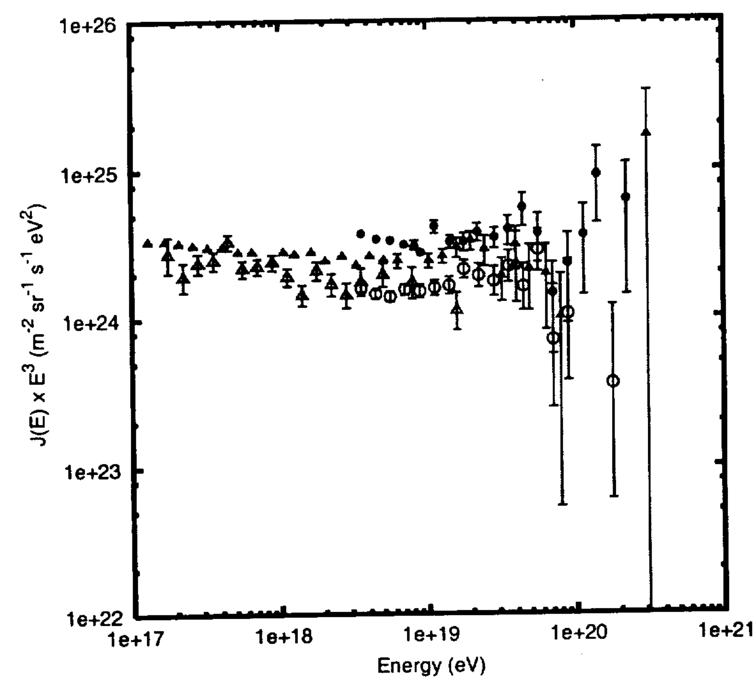

Figure 8. The ultrahigh energy cosmic ray spectral data from the analysis of *Fly's Eye* (closed triangles), *AGASA* (closed circles), *HiRes* I-monocular (open circles), and *HiRes* II-monocular (open triangles) observations.

al. 1998) is evidence for a new component of cosmic rays dominating above 10 EeV energy.

The apparent isotropy (no galactic-plane enhancement) of cosmic rays above 10 EeV (*e.g.*, Takeda, *et al.* 1999), together with the difficulty of confining protons in the galaxy at 10 to 30 EeV energies, provide significant reasons to believe that the cosmic-ray component above 10 EeV is extragalactic in origin. As can be seen from Figure 8, this extragalactic component appears to extend to an energy of 300 EeV. Extention of this spectrum to higher energies is conceivable because such cosmic rays, if they exist, would be too rare to have been seen with present detectors. We will

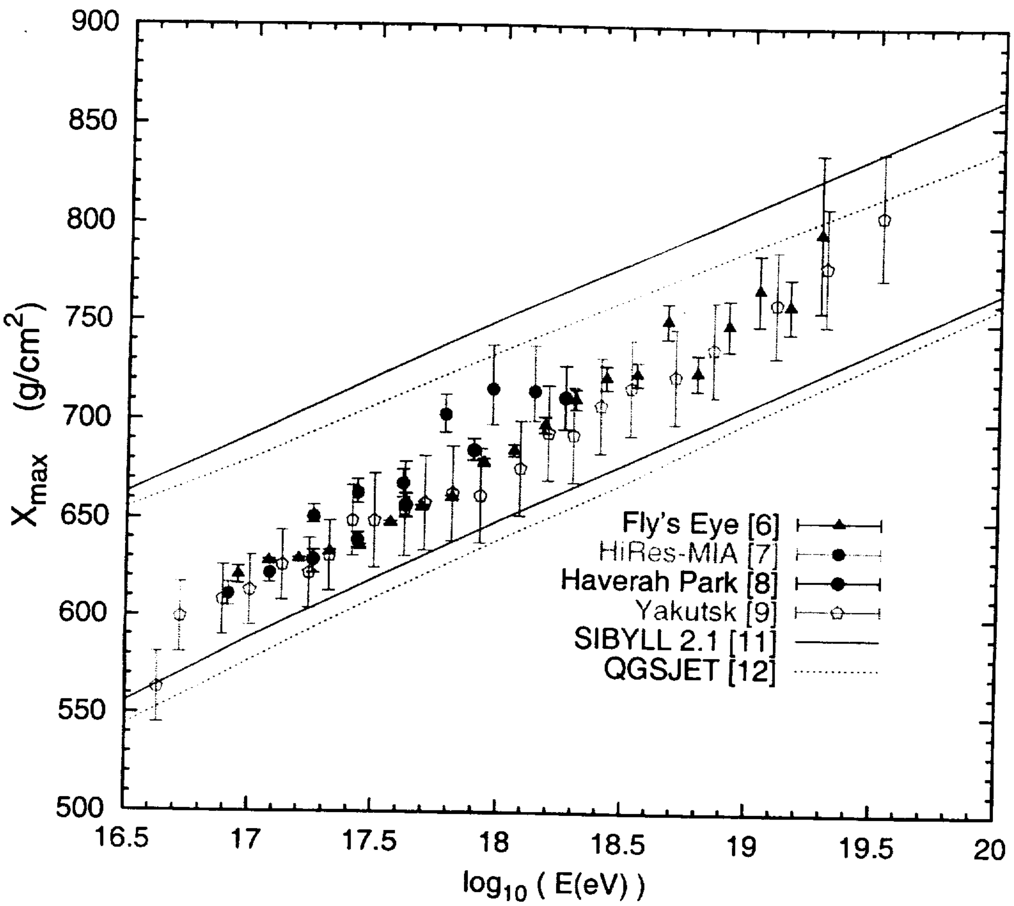

Figure 9. Average depth of shower maximum (X_{max}) *vs.* energy compared to the calculated values for protons (upper curves) and Fe primaries (lower curves) (from Gaisser 2000; see references therein).

see in the next section that the existence of 300 EeV cosmic rays gives us a new mystery to solve.

3.2. THE GZK EFFECT

Thirty seven years ago, Penzias and Wilson (1965) reported the discovery of the cosmic 2.7K thermal blackbody radiation which was produced very early on in the history of the universe and which led to the undisputed acceptance of the "big bang" theory of the origin of the universe. Much more recently, the *COBE* (Cosmic Background Explorer) satellite confirmed this discovery, showing that the cosmic background radiation (CBR) has

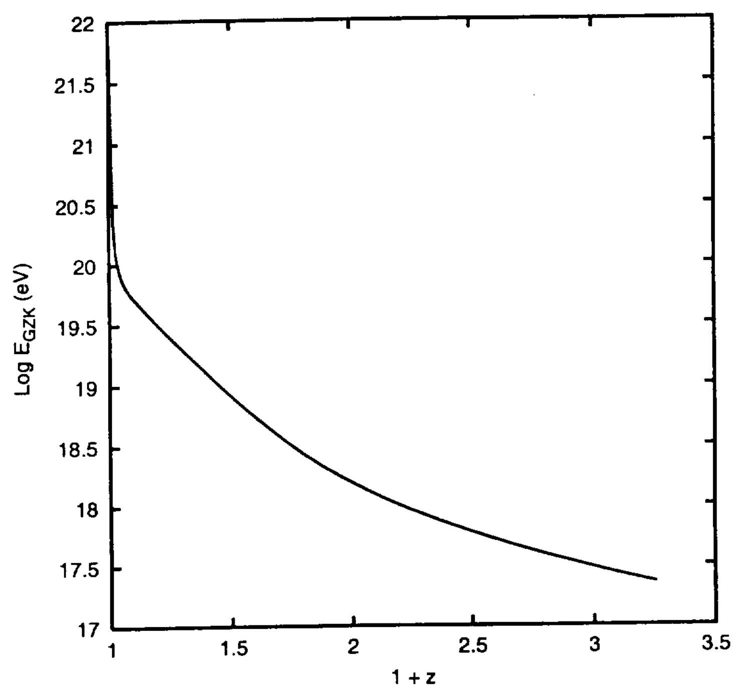

Figure 10. The GZK cutoff energy versus redshift (Scully and Stecker 2002).

the spectrum of the most perfect thermal blackbody known to man. *COBE* data also showed that this radiation (on angular scales > 7°) was isotropic to a part in 10^5 (Mather *et al.* 1994). The perfect thermal character and smoothness of the CBR proved conclusively that this radiation is indeed cosmological and that, at the present time, it fills the entire universe with a 2.725 K thermal spectrum of radio to far-infrared photons with a density of ~ 400 cm^{-3}.

Shortly after the discovery of the CBR, Greisen (1966) and Zatsepin and Kuz'min (1966)predicted that pion-producing interactions of ultrahigh energy cosmic ray protons with CBR photons of target density ~ 400 cm^{-3} should produce a cutoff in their spectrum at energies greater than ~ 50

EeV. This predicted effect has since become known as the GZK (Greisen-Zatsepin-Kuz'min) effect. Following the GZK papers, Stecker (1968) utilized data on the energy dependence of the photomeson production cross sections and inelasticities to calculate the mean energy loss time for protons propagating through the CBR in intergalactic space as a function of energy. Based on his results, Stecker (1968) then suggested that the particles of energy above the GZK cutoff energy (hereafter referred to as trans-GZK particles) must be coming from within the "Local Supercluster" of which we are a part and which is centered on the Virgo Cluster of galaxies. Thus, the "GZK cutoff" is not a true cutoff, but a supression of the ultrahigh energy cosmic ray flux owing to a limitation of the propagation distance to a few tens of Mpc.

The actual position of the GZK cutoff can differ from the 50 EeV predicted by Greisen (1966). In fact, there could actually be an *enhancement* at or near this energy owing to a "pileup" of cosmic rays starting out at higher energies and crowding up in energy space at or below the predicted cutoff energy (Puget, Stecker and Bredkamp 1976; Hill and Schramm 1985; Berezinsky and Grigor'eva 1988; Stecker 1989; Stecker and Salamon 1999). The existence and intensity of this predicted pileup depends critially on the flatness and extent of the source spectrum, (*i.e.*, the number of cosmic rays starting out at higher energies), but if its existence is confirmed in the future by more sensitive detectors, it would be evidence for the GZK effect.

Scully and Stecker (2002) have determined the GZK energy, defined as the energy for a flux decrease of $1/e$, as a function of redshift. At high redshifts, the target photon density increases by $(1+z)^3$ and both the photon and initial cosmic ray energies increase by $(1+z)$. The results obtained by Scully and Stecker are shown in Figure 10.

Figure 11 gives further results of Scully and Stecker (2002) compared with the present data. It shows the *form* of the cosmic ray spectrum to be expected from sources with a uniform redshift distribution and sources which follow the star formation rate. The required normalization and spectral index determine the energy requirements of any cosmological sources which are invoked to explain the observations. Pileup effects and GZK cutoffs are evident in the theoretical curves in this figure. As can be seen in Figure 11, the present data appear to be statistically consistent with either the presence or absence of a pileup effect. Future data with much better statistics are required to determine such a spectral structure.

Whereas the *AGASA* results indicate a significant number of events at trans-GZK energies, the analysis of observations made with the *HiRes* monocular detector array show only one event significantly above 100 EeV and appear to be consistent with the GZK effect (Abu-Zayyad *et al.* 2002; see Figure 11 and section 3.7.)

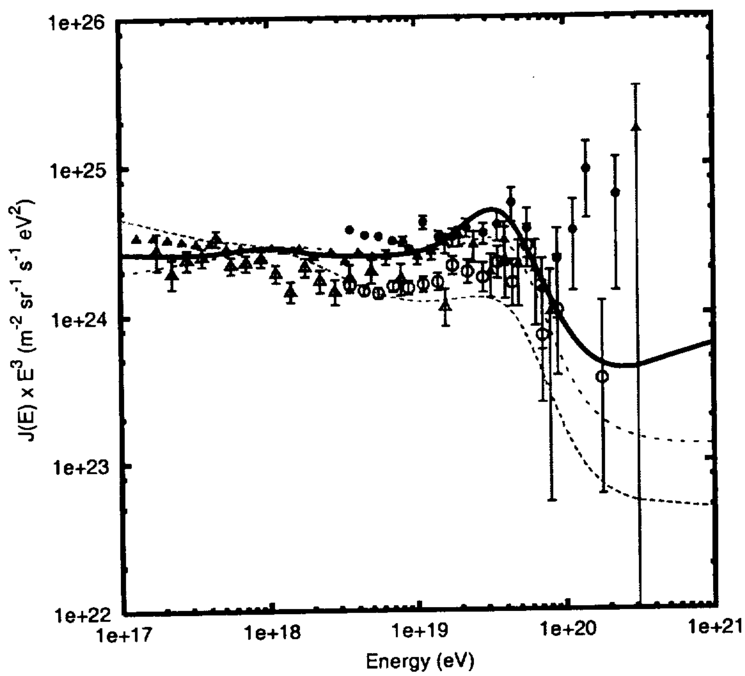

Figure 11. Predicted spectra for cosmic ray protons as compared with the data. The middle curve and lowest curve assume an $E^{-2.75}$ source spectrum with a uniform source distribution and one that follows the z distribution of the star formation rate respectively. The upper curve is for an $E^{-2.35}$ source spectrum which requires an order of magnitude more energy input and exhibits a "pileup effect".

3.3. ACCELERATION AND ZEVATRONS: THE "BOTTOM UP" SCENARIO

The apparent lack of a GZK cutoff (with the exception of the new *HiRes* results) has led theorists to go on a hunt for nearby "zevatrons", *i.e.*, astrophysical sources which can accelerate particles to energies $\mathcal{O}(1 \text{ ZeV} = 10^{21}\text{eV})$.

In most theoretical work in cosmic ray astrophysics, it is generally assumed that the diffusive shock acceleration process is the most likely mechanism for accelerating particles to high energy. (See, *e.g.*, Jones (2000) and

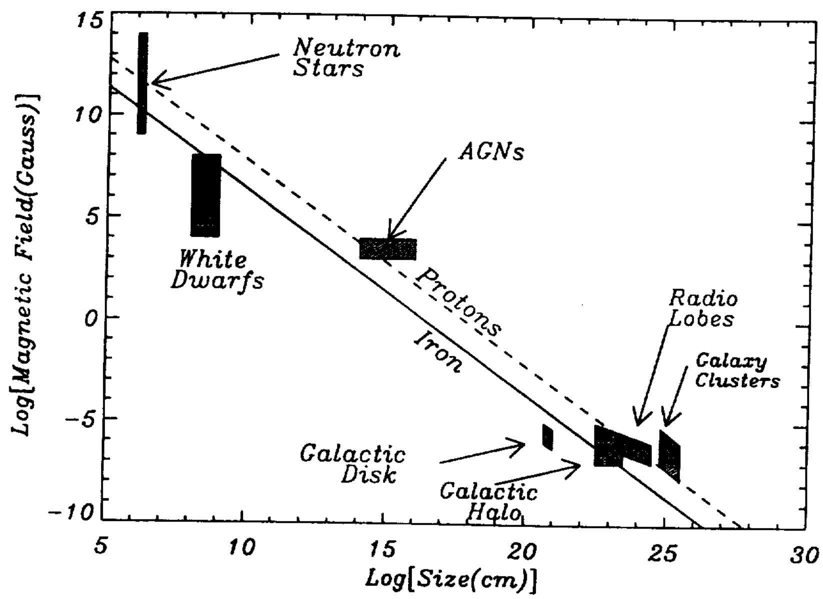

Figure 12. A "Hillas Plot" showing potential astrophysical zevatrons (from Olinto 2000). The lines are for B *vs.* L for $E_{max} = 0.1$ ZeV for protons and iron nuclei as indicated.

references therein.) In this case, the maximum obtainable energy is given by $E_{max} = keZ(u/c)BL$, where $u \leq c$ is the shock speed, eZ is the charge of the particle being accelerated, B is the magnetic field strength, L is the size of the accelerating region and the numerical parameter $k = \mathcal{O}(1)$ (Drury 1994). Taking $k = 1$ and $u = c$, one finds

$$E_{max} = 0.9Z(BL)$$

with E in EeV, B in μG and R in kpc. This assumes that particles can be accelerated efficiently up until the moment when they can no longer be contained by the source, *i.e.* until their gyroradius becomes larger than the size of the source. Hillas (1984) used this relation to construct a plot of B *vs.* L for various candidate astrophysical objects. A "Hillas plot" of this kind, recently constructed by Olinto (2000), is shown in Figure 12.

Given the relationship between E_{max} and BL as shown in Figure 12., there are not too many astrophysical candidates for zevatrons. Of these, galactic sources such as white dwarfs, neutron stars, pulsars, and magnetars can be ruled out because their galactic distribution would lead to anisotropies above 10 EeV which would be similar to those observed at lower energies by Hayashida *et al.* (1999), and this is not the case. Perhaps the most promising potential zevatrons are radio lobes of strong radio galaxies

(Biermann and Strittmatter (1987). The trick is that such sources need to be found close enough to avoid the GZK cutoff (*e.g.*, Elbert and Sommers 1995) Biermann has further suggested that the nearby radio galaxy M87 may be the source of the observed trans-GZK cosmic rays (see also Stecker 1968; Farrar and Piran 2000). Such an explanation would require one to invoke magnetic field configurations capable of producing a quasi-isotropic distribution of $> 10^{20}$ eV protons, making this hypothesis questionable. However, if the primary particles are nuclei, it is easier to explain a radio galaxy origin for the two highest energy events (Stecker and Salamon 1999; see section 3.4).

3.3.1. *The Dead Quasar Origin Hypothesis*

It has been suggested that since all large galaxies are suspected to harbor supermassive black holes in their centers which may have once been quasars, fed by accretion disks which are now used up, that nearby quasar remnants may be the searched-for zevatrons (Boldt and Ghosh 1999; Boldt and Lowenstein 2000). This scenario also has potential theoretical problems and needs to be explored further. In particular, it has been shown that black holes which are not accreting plasma cannot possess a large scale magnetic field with which to accelerate particles to relativistic energies (Ginzburg and Ozernoi 1964; Krolik 1999; Jones 2000). Observational evidence also indicates that the cores of weakly active galaxies have low magnetic fields (Falcke 2001 and references therein). Another proposed zevatron, the γ-ray burst, is discussed in the next section.

3.3.2. *The Cosmological Gamma-Ray Burst Origin Hypothesis*

In 1995, it was hypothesized that cosmological γ-ray bursts (GRBs) could be the zevatron sources of the highest energy cosmic rays (Waxman 1995; Vietri 1995). It was suggested that if these objects emitted the same amount of energy in ultrahigh energy ($\sim 10^{14}$ MeV) cosmic rays as in $\sim$ MeV photons, there would be enough energy input of these particles into intergalactic space to account for the observed flux. At that time, it was assumed that the GRBs were distributed uniformly, independent of redshift.

Since 1997, X-ray, optical, and radio afterglows of more than two dozen GRBs have been detected leading to the subsequent identification of the host galaxies of these objects and consequently, their redshifts. To date, some 27 GRBs afterglows have been detected with a subsequent identification of their host galaxies. As of this writing, 26 of the 27 are at moderate to high redshifts (> 0.36), with the highest one (GRB000131) lying at a redshift of 4.50.

A good argument in favor of strong redshift evolution for the frequency of occurrence of the higher luminosity GRBs has been made by Mao and

Mo (1998), based on the star-forming nature of the host galaxies. The host galaxies of GRBs appear to be sites of active star formation. The colors and morphological types of the host galaxies are indicative of ongoing star formation, as is the detection of Lyα and [OII] in several of these galaxies. Further evidence suggests that bursts themselves are directly associated with star forming regions within their host galaxies; their positions correspond to regions having significant hydrogen column densities with evidence of dust extinction. It now seems reasonable to assume that a more appropriate redshift distribution to take for GRBs is that of the average star formation rate. Results of the analysis of Schmidt (1999) also favor a GRB redshift distribution which follows the strong redshift evolution of the star formation rate. Thus, it now seems reasonable to assume that a more appropriate redshift distribution to take for GRBs is that of the average star formation rate, rather than a uniform distribution. If we thus assume a redshift distribution for the GRBs which follows the star formation rate, being significantly higher at higher redshifts, GRBs fail by at least an order of magnitude to account for the observed cosmic rays above 100 EeV (Stecker 2000).If one wishes to account for the GRBs above 10 EeV, this hypothesis fails by two to three orders of magnitude (Scully and Stecker 2002). Even these numbers are most likely too optimistic, since they are based on the questionable assumption of the same amount of GRB energy being put into ultrahigh energy cosmic rays as in $\sim$ MeV photons.

3.3.3. *Low Luminosity Gamma-Ray Bursts*

An unusual nearby Type Ic supernova, SN 1998bw, at a redshift of 0.0085, has been identified as the source of a low luminosity burst, GRB980425, with an energy release which is orders of magnitude smaller than that for a typical cosmological GRB. Norris (2002) has given an analysis of the luminosities and space densities of such nearby low luminosity long-lag GRB sources which are identified with Type I supernovae. For these sources, he finds a rate per unit volume of 7.8×10^{-7} Mpc^{-3}yr^{-1} and an average (isotropic) energy release per burst of 1.3 $\times 10^{49}$ erg over the energy range from 10 to 1000 keV. The energy release per unit volume is then $\sim 10^{43}$ erg Mpc^{-3}yr^{-1}. This rate is more than an order of magnitude below the rate needed to account for the cosmic rays with energies above 10 EeV.

3.4. THE HEAVY NUCLEI ORIGIN SCENARIO

A more conservative hypothesis for explaining the trans-GZK events is that they were produced by heavy nuclei. Stecker and Salamon (1999) have shown that the energy loss time for nuclei starting out as Fe is longer than that for protons for energies up to a total energy of $\sim$300 EeV (See Figure

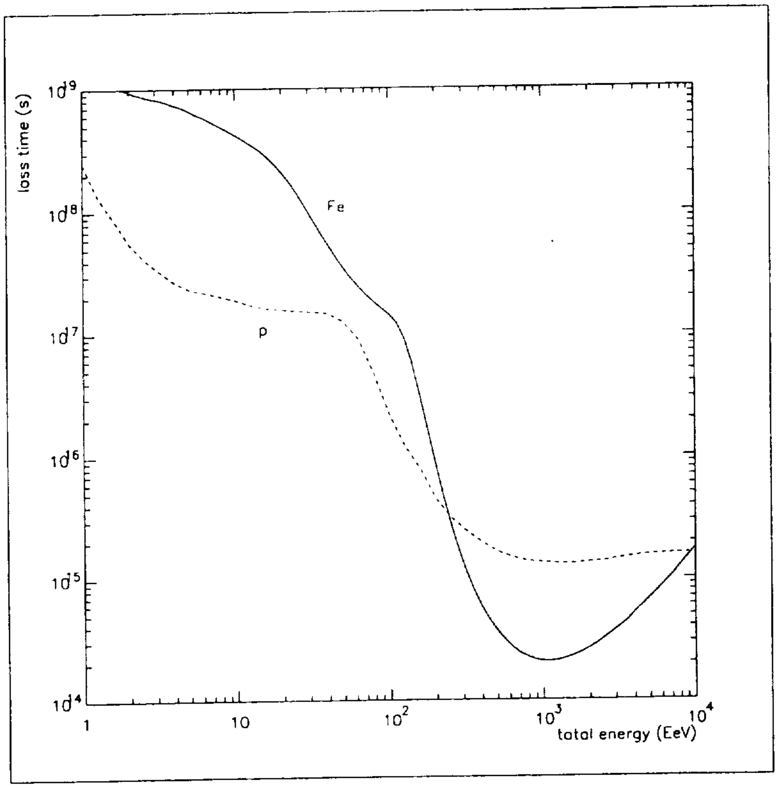

Figure 13. Mean energy loss times for protons (Stecker 1968; Puget, Stecker and Bredekamp 1976) and nuclei originating as Fe (Stecker and Salamon 1999).

13.)

Stanev *et al.* (1995) and Biermann (1998) have examined the arrival directions of the highest energy events.They point out that the $\sim$ 200 EeV event is within 10° of the direction of the strong radio galaxy NGC 315. This galaxy lies at a distance of only $\sim$ 60 Mpc from us. For that distance, the results of Stecker and Salamon (1999) indicate that heavy nuclei would have a cutoff energy of $\sim$ 130 EeV, which may be within the uncertainty in the energy determination for this event. The $\sim$300 EeV event is within 12° of the direction of the strong radio galaxy 3C134. The distance to 3C134 is unfortunately unknown because its location behind a dense molecular cloud in our own galaxy obscures the spectral lines required for a measurement of its redshift.

An interesting new clue that we may indeed be seeing heavier nuclei above the proton-GZK cutoff comes from a recent analysis of inclined air showers above 10 EeV energy (Ave, *et al.* 2000). These new results favor proton primaries below the p-GZK cutoff energy but they *appear to favor a heavier composition above the p-GZK cutoff energy.* It will be interesting to see what future data from much more sensitive detectors will tell us.

3.5. TOP-DOWN SCENARIOS: "FRAGGERS"

A way to avoid the problems with finding plausible astrophysical zevatrons is to start at the top, *i.e.*, the energy scale associated with grand unification, supersymmetric grand unification or its string theory equivalent.

The modern scenario for the early history of the big bang takes account of the work of particle theorists to unify the forces of nature in the framework of Grand Unified Theories (GUTs) (*e.g.*, , Georgi and Glashow 1974). This concept extends the very successful work of Nobel Laureates Glashow, Weinberg, and Salam in unifying the electromagnetic and weak nuclear forces of nature (Glashow 1960; Weinberg 1967; Salam 1968). As a consequence of this theory, the electromagnetic and weak forces would have been unified at a higher temperature phase in the early history of the universe and then would have been broken into separate forces through the mechanism of spontaneous symmetry breaking caused by vacuum fields which are known as Higgs fields.

In GUTs, this same paradigm is used to infer that the electroweak force becomes unified with the strong nuclear force at very high energies of $\sim 10^{24}$ eV which occurred only $\sim 10^{-35}$ seconds after the big bang. The forces then became separated owing to interactions with the much heavier mass scale Higgs fields whose symmetry was broken spontaneously. The supersymmetric GUTs (or SUSY GUTs) provide an explanation for the vast difference between the two unification scales (known as the "Hierarchy Problem") and predict that the running coupling constants which describe the strength of the various forces become equal at the SUSY GUT scale of $\sim 10^{24}$ eV (Dimopoulos, Raby and Wilczek 1982).

3.5.1. *Topological Defects: Fossils of the Grand Unification Era*

Very heavy "topological defects" can be produced as a consequence of the GUT phase transition when the strong and electroweak forces became separated. These defects are localized regions of vacuum Higgs fields where extremely high densities of mass-energy are trapped.

Topological defects in the vacuum of space are caused by misalignments of the heavy Higgs fields in regions which were causally disconnected in the early history of the universe. These are localized regions where extremely high densities of mass-energy are trapped. Such defects go by designations such as cosmic strings, monopoles, walls, necklaces (strings bounded by monopoles), and textures, depending on their geometrical and topological properties. Inside a topological defect vestiges of the early universe may be preserved to the present day. The general scenario for creating topological defects in the early universe was suggested by Kibble (1976).

Superheavy particles or topological structures arising at the GUT energy scale $M \geq 10^{23}$ eV can decay or annihilate to produce "X-particles" (GUT scale Higgs particles, superheavy fermions, or leptoquark bosons of mass M.) In the case of strings this could involve mechanisms such as intersecting and intercommuting string segments and cusp evaporation. These X-particles will decay to produce QCD fragmentation jets at ultrahigh energies, so I will refer to them as "fraggers". QCD fraggers produce mainly pions, with a 3 to 10 per cent admixture of baryons, so that generally one can expect them to produce at least an order of magnitude more high energy γ-rays and neutrinos than protons. The same general scenario would hold for the decay of long-lived superheavy dark matter particles (see section 3.8), which would also be fraggers. It has also been suggested that the decay of ultraheavy particles from topological defects produced in SUSY-GUT models which can have an additional soft symmetry breaking scale at TeV energies ("flat SUSY theories") may help explain the observed γ-ray background flux at energies $\sim$ 0.1 TeV (Bhattacharjee, Shafi and Stecker 1998).

The number of variations and models for explaining the ultrahigh energy cosmic rays based on the GUT or SUSY GUT scheme (which have come to be called "top-down" models) has grown to be enormous and I will not attempt to list all of the numerous citations involved. Fortunately, Bhattacharjee and Sigl (2000) have published an extensive review with over 500 citations and I refer the reader to this review for further details of "top-down" models and references. The important thing to note here is that, if the implications of such models are borne out by future cosmic ray data, they may provide our first real evidence for GUTs.

3.5.2. *"Z-bursts"*

It has been suggested that ultra-ultrahigh energy $\mathcal{O}(10$ ZeV) neutrinos can produce ultrahigh energy Z^0 fraggers by interactions with 1.9K thermal CBR neutrinos (Weiler 1982; Fargion *et al.* 1999; Weiler 1999), () resulting in "Z-burst" fragmentation jets, again producing mostly pions. This will occur at the resonance energy $E_{res} = 4[m_\nu(\text{eV})]^{-1}$ ZeV. A typical Z boson will decay to produce $\sim$2 nucleons, $\sim$20 γ-rays and $\sim$ 50 neutrinos, 2/3 of which are ν_μ's.

If the nucleons which are produced from Z-bursts originate within a few tens of Mpc of us they can reach us, even though the original $\sim$ 10 ZeV neutrinos could have come from a much further distance. It has been suggested that this effect can be amplified if our galaxy has a halo of neutrinos with a mass of tens of eV (Fargion, Mele and Salis 1999; Weiler 1999). However, a neutrino mass large enough to be confined to a galaxy size neutrino halo (Tremaine and Gunn 1979) would imply a hot dark matter cosmology which is inconsistent with simulations of galaxy formation and clustering (*e.g.*, Ma and Bertschinger 1994) and with angular fluctuations in the CBR. (Another problem with halo fraggers is discussed below in section 3.9) A mixed dark matter model with a lighter neutrino mass (Shafi and Stecker 1984) produces predicted CBR angular fluctuations (Schaefer, Shafi and Stecker 1989) which are consistent with the *Cosmic Background Explorer* data (Wright 1992). In such a model, neutrinos would have density fluctuations on the scale of superclusters, which would still allow for some amplification (Weiler 1999). The tritium decay spectral endpoint limits on the mass of the electron neutrino (Weinheimer *et al.* 1999), together with the very small neutrino flavor mass differences indicated by the atmospheric and solar neutrino oscillation results (Fukuda *et al.* 1998, 1999; Smy 2002; Ahmad *et al.* 2002; Bandyopadhyay *et al.* 2002) constrains all neutrino flavors to have masses in the range $\mathcal{O}$(eV) or less. This is much too small a mass for neutrinos to to be confined to halos of individual galaxies.

The basic general problem with the Z-burst explanation for the trans-GZK events is that one needs to produce 10 ZeV neutrinos. If these are secondaries from pion production, this implies that the primary protons which produce them must have energies of hundreds of ZeV! Since we know of no astrophysical source which would have the potential of accelerating particles to energies even an order of magnitude lower (see section 4), a much more likely scenario for producing 10 ZeV neutrinos would be by a top-down process. The production rate of neutrinos from such processes is constrained by the fact that the related energy release into electromagnetic cascades which produce GeV range γ-rays is limited by the satellite observations (see the review by Bhattacharjee and Sigl 2000). This constraint, together with the low probability for Z-burst production, relegates the Z-burst phenomenon to a minor secondary role at best.

3.5.3. *Ultraheavy Dark Matter Particles: "Wimpzillas"*

The homogeneity and flatness of the present universe may imply that a period of very rapid expansion, called inflation, took place shortly after the big bang. The early inflationary phase in the history of the universe can lead to the production of ultrahigh energy neutrinos. The inflation of the early universe is postulated to be controlled by a putative vacuum field called the inflaton field. During inflation, the universe is cold but, when inflation is over, coherent oscillations of the inflaton field reheat it to a high temperature. While the inflaton field is oscillating, non-thermal production of very heavy particles ("wimpzillas") may take place. These heavy particles may survive to the present as a part of the dark matter. Their decays will produce ultrahigh energy particles and photons *via* fragmentation.

It has been suggested that such particles may be the source of ultrahigh energy cosmic rays (Berezinsky *et al.* 1997; Kuz'min and Rubakov 1998; Blasi *et al.* 2002; Sarkar and Toldrà 2002; Barbot and Drees 2002). The annihilation or decay of such particles in a dark matter halo of our galaxy would produce ultrahigh energy nucleons which would not be attenuated at trans-GZK energies owing to their proximity.

3.5.4. *Halo Fraggers and the Missing Photon Problem*

Halo fragger models such as Z-burst and ultraheavy halo dark matter ("wimpzilla") decay or annihilation, as we have seen, will produce more ultrahigh energy photons than protons. These ultrahigh energy photons can reach the Earth from anywhere in a dark matter galactic halo, because, as shown in Figure 7, there is a "mini-window" for the transmission of ultrahigh energy cosmic rays between ~ 0.1 and $\sim 10^6$ EeV.

Photon-induced giant air showers have an evolution profile which is significantly different from nucleon-induced showers because of the Landau-Pomeranchuk-Migdal (LPM) effect (Landau and Pomeranchuk 1953; Migdal 1956) and because of cascading in the Earth's magnetic field (Cillis *et al.* 1999) (see Figure 7). By taking this into account, Shinozaki, *et al.* (2002) have used the AGASA data to place upper limits on the photon composition of their UHECR showers. They find a photon content upper limit of 28% for events above 10 EeV and 67% for events above 30 EeV at a 95% confidence level with no indication of photonic showers above 100 EeV. A recent reanalysis of the ultrahigh energy events observed at Haverah Park by Ave, *et al.* (2002) indicates that less than half of the events (at 95% confidence level) observed above 10 and 40 EeV are γ-ray initiated. An analysis of the highest energy Fly's Eye event ($E = 300$ EeV) shows it not to be of photonic origin, as indicated in Figure 15. In addition, Shinozaki, *et al.* (2002) have found no indication of departures from isotropy as would be expected from halo fragger photonic showers, this admittedly with only 10 events in their sample.

3.6. OTHER NEW PHYSICS POSSIBILITIES

The GZK cutoff problem has stimulated theorists to look for possible solutions involving new physics. Some of these involve (A) a large increase in the neutrino-nucleon cross section at ultrahigh energies, (B) new particles, and (C) a small violation of Lorentz Invariance (LI).

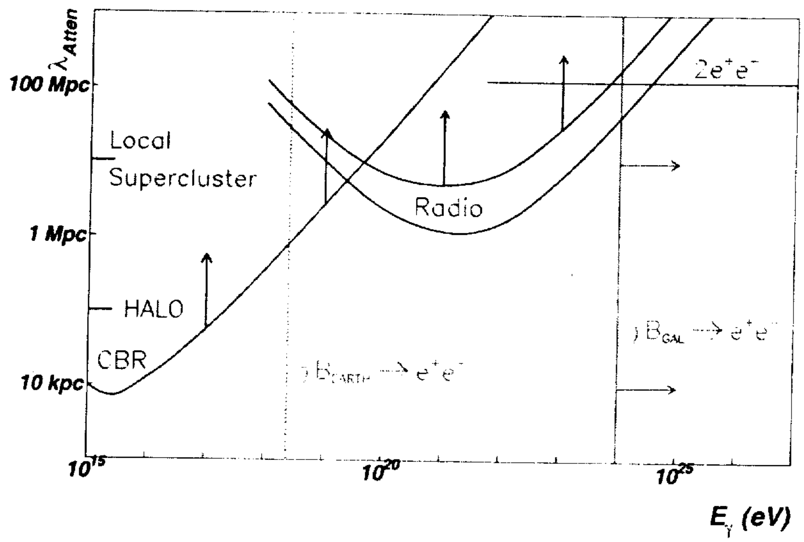

Figure 14. The mean free path for ultrahigh energy γ-ray attenuation *vs.* energy. The curve for electron-positron pair production off the cosmic background radiation (CBR) is based on Gould and Schréder (1966). The two estimates for pair production off the extragalactic radio background are from Protheroe and Biermann (1996). The curve for double pair production is based on Brown, *et al.* (1973). The physics of pair production by single photons in magnetic fields is discussed by Erber (1966). This process eliminates all photons above $\sim 10^{24}$ eV and produces a terrestrial anisotropy in the distribution of photon arrival directions above $\sim 10^{19}$eV.

3.6.1. *Increasing the Neutrino-Nucleon Cross Section at Ultrahigh Energies*

Since neutrinos can travel through the universe without interacting with the 2.7K CBR, it has been suggested that if the neutrino-nucleon cross section were to increase to hadronic values at ultrahigh energies, they could produce the giant air showers and account for the observations of showers above the proton-GZK cutoff. Several suggestions have been made for processes that can enhance the neutrino-nucleon cross section at ultrahigh energies. These suggestions include composite models of neutrinos (Domokos and Nussinov 1987; Domokos and Kovesi-Domokos 1988), scalar leptoquark resonance channels (Robinett 1988) and the exchange of dual gluons (Bordes, *et al.* 1998).Burdman, Halzen and Gandhi (1998) have ruled out a fairly general class of these types of models, including those listed above, by pointing out that in order to increase the neutrino-nucleon cross section to hadronic values at $\sim 10^{20}$ eV without violating unitarity bounds, the relevant scale of compositeness or particle exchange would have to be of the order of a GeV, and that such a scale is ruled out by accelerator experiments.

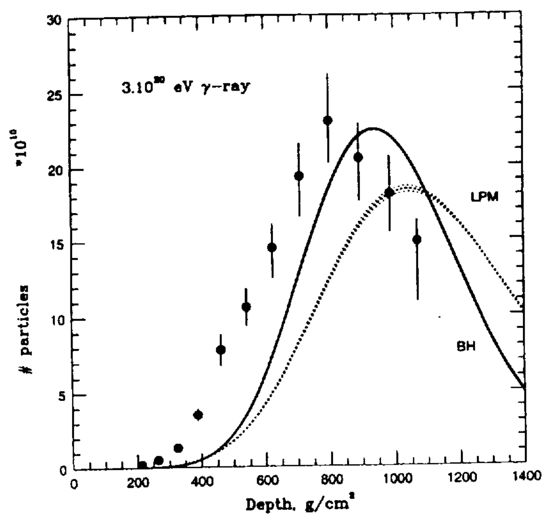

Figure 15. The composite atmospheric shower profile of a 300 EeV photon-induced shower calculated with the Bethe-Heitler (solid) electromagnetic cross section and with the LPM effect taken into account (dashed line, see text). The measured Fly's Eye profile, which fits the profile of a nucleonic primary, is shown by the data points (Halzen and Hooper 2002).

More recently, the prospect of enhanced neutrino cross sections has been explored in the context of extra dimension models. Such models have been suggested by theorists to unify the forces of physics since the days of Kaluza (1921) and Klein (1926). In recent years, they have been invoked by string theorists and by other theorists as a possible way for accounting for the extraordinary weakness of the gravitational force, or, in other words, the extreme size of the Planck mass (Arkani-Hamed, Dimopoulos and Dvali 1999; Randall and Sundrum 1999). These models allow the virtual exchange of gravitons propagating in the bulk (*i.e.* in the space of full extra dimensions) while restricting the propagation of other particles to the familiar four dimensional space-time manifold. It has been suggested that in such models, $\sigma(\nu N) \simeq [E_\nu/(10^{20}\mathrm{eV})]$ mb (Nussinov and Schrock 1999; Jain, *et al.* 2000; see also Domokos and Kovesi-Domokos 1999). It should be noted that a cross section of $\sim$ 100 mb would be necessary to approach obtaining consistency with the air shower profile data. Other scenarios involve the neutrino-initiated atmopheric production of black holes (Anchordoqui *et al.* 2002) and even higher dimensional extended objects, p-dimensional branes called "p-branes" (Ahn, Cavaglia and Olinto 2002; Anchordoqui, Feng and Goldberg 2002). Such interactions, in principle, can increase the neutrino total atmospheric interaction cross section by orders of magnitude above the standard model value. However, as discussed by Anchordoqui, Feng and Goldberg (2002), sub-mm gravity experiments and astrophysical constraints rule out total neutrino interaction cross sections as large as 100 mb as would be needed to fit the trans-GZK energy air shower profile data. Nonetheless, extra dimension models still may lead to significant increases in the neutrino cross section, resulting in moderately penetrating air showers. Such neutrino-induced showers should also be present at somewhat lower energies and provide an observational test for extra dimension TeV scale gravity models (Anchordoqui *et al.* 2001; Tyler, Olinto and Sigl 2001). As of this writing, no such showers have been observed, putting an indirect constraint on fragger scenarios with TeV gravity models.

3.6.2. *New Particles*

The suggestion has also been made that new neutral particles containing a light gluino could be producing the trans-GZK events (Farrar 1996; Cheung, Farrar and Kolb 1998).While the invocation of such new particles is an intriguing idea, it seems unlikely that such particles of a few proton masses would be produced in copious enough quantities in astrophysical objects without being detected in terrestrial accelerators. Also there are now strong constraints on gluinos (Alavi-Harati, *et al.* 1999). One should note that while it is true that the GZK threshold for such particles would be higher than that for protons, such is also the case for the more prosaic heavy nuclei (see section 3.4). In addition, such neutral particles cannot be accelerated directly, but must be produced as secondary particles, making the energetics reqirements more difficult.

3.6.3. *Breaking Lorentz Invariance*

With the idea of spontaneous symmetry breaking in particle physics came the suggestion that Lorentz invariance (LI) might be weakly broken at high energies (Sato and Tati 1972). Although no real quantum theory of gravity exists, it was suggested that LI might be broken as a consequence of such a theory (Amelino-Camilia *et al.* 1998). A simpler formulation for breaking LI by a small first order perturbation in the electromagnetic Lagrangian which leads to a renormalizable treatment has been given by Coleman and Glashow (1999). Using this formalism, these authors have shown than only a very tiny amount of LI symmetry breaking is required to avoid the GZK effect by supressing photomeson interactions between ultrahigh energy protons and the CBR. This LI breaking amounts to a difference of $\mathcal{O}(10^{-23})$ between the maximum proton pion velocities. By comparison, Stecker and Glashow (2001) have placed an upper limit of $\mathcal{O}(10^{-13})$ on the difference between the velocities of the electron and photon, ten orders of magnitude higher than required to eliminate the GZK effect.

3.7. IS THE GZK EFFECT ALL THERE IS?

There is a remaining "dull" possibility. Perhaps the GZK effect is consistent with the data and is all there is at ultrahigh energies. The strongest case for trans-GZK physics comes from the *AGASA* results. The *AGASA* group, which reported up to 17 events with energy greater than or equal to $\sim$ 100 EeV (Sasaki *et al.* 2001), has now lowered this number to 8 (see footnote 1). However, the *HiRes* Group have not confirmed the *AGASA* results; the *HiRes* results imply lower fluxes of cosmic rays above $\sim$ 100 EeV which are consistent with the GZK effect (Abu-Zayyad *et al.* 2002; see Figure 11.) We note, however, that even if the GZK effect is seen, top-down scenarios predict the reemergence of a new component at even higher energies (Aharonian, Bhattacharjee and Schramm 1992; Bhattacharjee and Sigl 2000).

The *AGASA* data indicate a significant deviation from pure GZK even if the source number is weighted like the local galaxy distribution (Blanton, *et al.* 2001.) In addition to this discrepency, the fact that a flourescence detector, Fly's Eye, reported the highest energy event yet seen, it viz., $E \simeq$ 300 EeV, makes the experimental situation interesting enough to justify both more sensitive future detectors and the exploration of new physics and astrophysics. In this regard, we note that the *Auger* detector array will use both scintillators and flourscence detectors (Zas 2001; see section 5.) Therefore, combined results from this detector array can help clarify the present discrepency between the *AGASA* and *HiRes* results.

3.8. ULTRAHIGH ENERGY EVENT SIGNATURES

Future data which will be obtained with new detector arrays and satellites (see next section) will give us more clues relating to the origin of the trans-GZK events by distinguishing between the various hypotheses which have been proposed.

A zevatron origin ("bottom-up" scenario) will produce air-showers primarily from primaries which are protons or heavier nuclei, with a much smaller number of neutrino-induced showers. The neutrinos will be secondaries from the photomeson interactions which produce the GZK effect (Stecker 1973; 1979; Engel, Seckel and Stanev 2001 and references therein). In addition, zevatron events may cluster near the direction of the sources.

A "top-down" (GUT) origin mechanism will not produce any heavier nuclei and will produce more ultrahigh energy neutrinos than protons. This was suggested as a signature of top-down models by Aharonian, Bhatacharjee and Schramm (1992). Thus, it will be important to look for the neutrino-induced air showers which are expected to originate much more deeply in the atmosphere than proton-induced air showers and are therefore expected to be mostly horizontal showers. Looking for these events can most easily be done with a satellite array which scans the atmosphere from above (see Section 4.)

Top-down models also produce more photons than protons. However, the mean free path of these photons against pair-production interactions with extragalactic low frequency radio photons from radio galaxies is only a few Mpc at most (Protheroe and Biermann 1996). The subsequent electromagnetic cascade and synchrotoron emission of the high energy electrons produced in the cascade dumps the energy of these particles into much lower energy photons (Wdowczyk, Tkaczyk and Wolfendale 1972; Stecker 1973). However, the photon-proton ratio is an effective tool for testing halo fragger models (See sect. 3.9.)

Another characteristic which can be used to distinguish between the bottom-up and top-down models is that the latter will produce much harder spectra. If differential cosmic ray spectra are parametrized to be of the form $F \propto E^{-\Gamma}$, then for top-down models $\Gamma < 2$, whereas for bottom-up models $\Gamma \geq 2$. Also, because of the hard source spectrum in the "top-down" models, they should exhibit both a GZK suppression and a pileup just before the GZK energy.

If Lorentz invariance breaking is the explanation for the missing GZK effect, the actual absence of photomeson interactions should result the absence of a pileup effect as well.

4. Ultrahigh Energy Cosmic Ray Neutrinos

Astronomy at the highest energies observed must be performed by studying neutrinos rather than photons because the universe is opaque to photons originating at redshift z at energies above $100(1+z)^{-2}$ TeV owing to interactions with the 2.7 K radiation (Stecker 1969) and even lower energies owing to interactions with other sources of extragalactic radiation (see section 2.4.) On the other hand, the cross section for neutrino detection rises with energy (see, *e.g.*, Gandhi *et al.* 1998) making the detection of neutrinos easier at higher energies. Although no ultrahigh energy cosmic neutrinos have yet been seen, there are various potential production mechanisms and sources which may produce these particles and their study can yield important new information for physics, cosmology, and astrophysics.

4.1. NEUTRINOS FROM INTERACTIONS OF ULTRAHIGH ENERGY COSMIC RAYS WITH THE 3 K COSMIC BACKGROUND RADIATION

Measurements from the *COBE* (Cosmic Background Explorer) convincingly proved that the universe is filled with radiation having the character of a near-perfect 2.725 K black body, which is a remnant of the big-bang. As

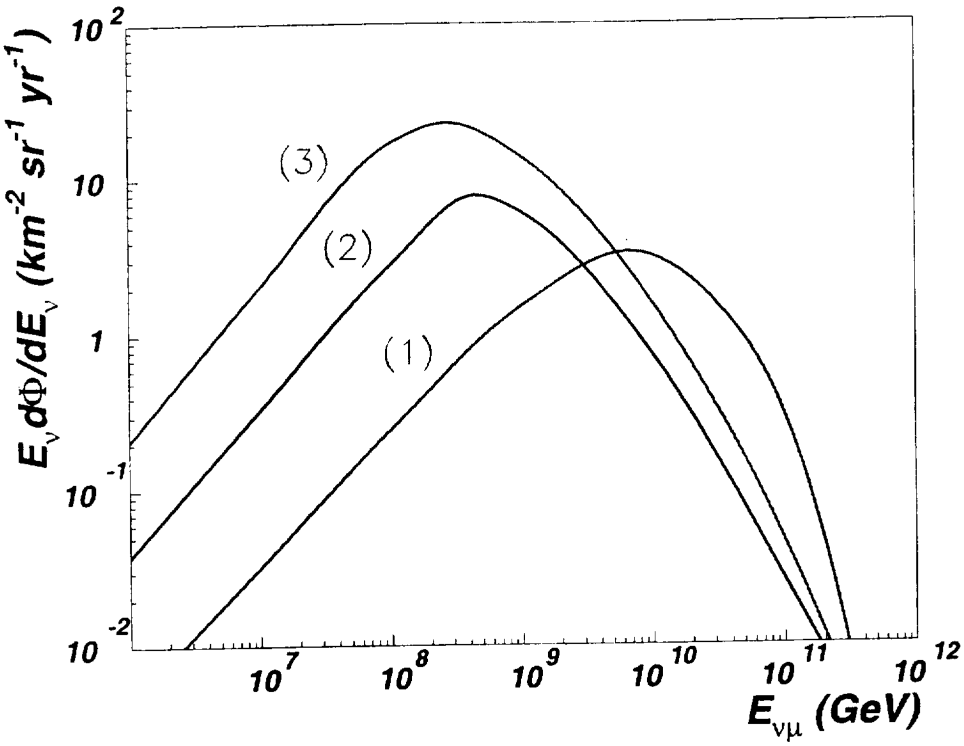

Figure 16. The ν_μ flux from photomeson production *via* $p\gamma_{2.7K}$ followed by $\pi^\pm$ decay. Curve (1) is the calclated flux without redshift evolution obtained by Stecker (1979). The fluxes obtained by Engel *et al.* (2001) with redshift evolution of the proton sources $\propto (1+z)^m$ with m=3 and 4 respectively are given by curves (2) and (3).

discussed in section 3.2, protons having energies above 100 EeV will interact with photons of this radiation, producing pions (Greisen 1966; Zatsepin and Kuz'min 1966). Ultrahigh energy neutrinos will result from decay of these pions (Stecker 1973, 1979). The spectrum calculated by Stecker (1979) without ultrahigh energy source evolution is shown in Figure 16 along with two flux spectra assuming source evolution $\propto (1+z)^m$ calculated by Engel *et al.* (2001).

By extrapolating the present measurements of the flux of such high energy protons (see section 3), it can be shown that measurable numbers of high energy neutrinos can be detected using imaging optics aboard satellites looking down at the luminous tracks produced in the atmosphere by showers of charged particles produced when these neutrinos hit the nuclei of atoms in the atmosphere (see section 5).

4.2. NEUTRINOS FROM ACTIVE GALACTIC NUCLEI

Quasars and other active galactic nuclei (AGN) are most powerful continuous emitters of energy in the known universe. These remarkable objects are fueled by the gravitational energy released by matter falling into a supermassive black hole at the center of the quasar core. The infalling matter accumulates in an accretion disk which heats up to temperatures high enough to emit large amounts of UV and soft X-radiation. The mechanism responsible for the efficient conversion of gravitational energy to observed luminous energy in not yet completely understood. If this conversion occurs partly through the acceleration of particles to relativistic energies, perhaps by the shock formed at the inner edge of the accretion disk (Kazanas and Ellison 1986), then the interactions of the resulting high energy cosmic rays with the intense photon fields produced by the disk at the quasar cores can lead to the copious production of mesons. The subsequent decay of these mesons will then produce large fluxes of high energy neutrinos (Stecker *et al.* 1991; Stecker and Salamon 1996b). Since the γ-rays and high energy cosmic rays deep in the intense radiation field of the AGN core will lose their energy rapidly and not leave the source region, these AGN core sources will only be observable as high energy neutrino sources.

Radio loud quasars contain jets of plasma streaming out from the vicinity of the black hole, in many cases with relativistic velocities approaching the speed of light. In a subcategory of quasars, known as blazars, these jets are pointed almost directly at us with their observed radiation, from radio to γ-raywavelengths, beamed toward us (See sect. 2.3.) It has been found that most of these blazars actually emit the bulk of their energy in the high energy γ-ray range. If, as has been suggested, the γ-radiation from these objects is the result of interactions of relativistic nuclei (Mannheim and Biermann 1989; Mannheim 1993), then high energy neutrinos will be produced with energy fluxes comparable to the γ-ray fluxes from these objects. On the other hand, if the blazar γ-radiation is produced by purely electromagnetic processes involving only high energy electrons, then no neutrino flux will result.

4.3. NEUTRINOS FROM GAMMA-RAY BURSTS (GRBS)

GRBs are the most energetic transient phenomenon known in the universe. In a very short time of ~ 0.1 to 100 seconds, these bursts can release an energy in γ-rays alone of the order of 10^{52} erg. They are detected at a rate of about a thousand per year by present instruments. It has been proposed that particles can be accelerated in these bursts to energies in excess of 10^{20} eV by relativistic shocks (Waxman 1995; Vietri 1995).

It is now known that most bursts are at cosmological distances corresponding to moderate redshifts ($z \sim 1$). If cosmic-rays are accelerated in them to ultrahigh energies, interactions with γ-rays in the sources leading to the production of pions has been suggested as a mechanism for producing very high energy neutrinos as well (Waxman and Bahcall 1997; Mészáros and Waxman 2001). These neutrinos would also arrive at the Earth in a burst coincident with the γ-ray photons. This is particularly significant since the ultrahigh energy cosmic rays from moderate redshifts are attenuated by interactions with the 2.7 K microwave radiation from the big-bang and are not expected to reach the Earth themselves in significant numbers (Stecker 2000).

4.4. NEUTRINOS FROM TOPOLOGICAL DEFECTS AND DARK MATTER

Topological defects are expected to produce very heavy particles that decay to produce ultrahigh energy neutrinos. The annihilation and decay of these structures is predicted to produce large numbers of neutrinos with energies approaching the predicted energy of grand unification (*e.g.*, Bhattacharjee and Sigl 2000; see section 3.5.). The discovery of such a large flux of neutrinos with a hard spectrum and with energies approaching the energy scale predicted for grand unification would be *prima facie* evidence for a unified gauge theory of strong and electroweak interactions.

An early inflationary phase in the history of the universe can also lead to the production of ultrahigh energy neutrinos. Non-thermal production of very heavy particles ("wimpzillas") may take place. (See section 3.5.3.) These heavy particles may survive to the present as a part of dark matter. Their decays will produce ultrahigh energy particles and photons *via* fragmentation, including ultrahigh energy neutrinos (see, *e.g.*, Barbot *et al.* 2002.)

4.5. Z-BURST NEUTRINOS

The observed thermal 2.7 K cosmic background radiation which permeates the universe as a relic of the big-bang is accompanied by a 1.96 K cosmic neutrino background of the same thermal big-bang origin (see *e.g.*, Kolb and Turner 1990.) It has been proposed that high energy neutrinos interacting within the GZK attenuation distance with the copious 2 K blackbody neutrinos and annihilating at the Z-boson resonance energy can produce the observed "trans-GZK" air-shower events (Weiler 1982, see section 3.5.2.) The resulting Z-boson decays to produce a shower of leptons, photons and hadrons, a.k.a. a "Z-burst". Ultrahigh energy neutrinos are produced by the decay of the $\pi^{\pm}$'s in the Z-burst. Approximately 50 neutrinos are produced per burst event; 2/3 of them are ν_μ's. Because the annihilation process is resonant, the Z-burst energy is unique. It is $E_{Z-burst} = 4m_\nu(\mathrm{eV})^{-1}$ ZeV.

The Z-burst hypothesis is based on the assumption that there exists a significant flux of neutrinos at $E \sim 10$ ZeV, perhaps from topological defects. Some predictive consequences of this hypothesis are: (a) that the direction of the air showers should be close to the directions of the sources, (b) that there may be multiple events coming from the directions of the strongest sources, and (c) that there exists a relationship between the maximum shower energy attainable and the terrestrially-measured neutrino mass,

As was discussed in section 3.5.2, this production mechanism is quite speculative at best.

4.6. NEUTRINO OSCILLATIONS AND TAU-NEUTRINO OBSERVATONS

Recent observations of the disappearance of atmospheric ν_μ's relative to ν_e's by the Kamiokande group and also the zenith angle distribution of this effect (Fukuda *et al.* 1998, 1999), may be interpreted as evidence of the oscillation of this weakly interacting neutrino state ("flavor") into another neutrino flavor, either ν_τ's or sterile neutrinos. A corollary of such a conclusion is that at least one neutrino state has a finite mass. This has very important consequences for our basic theoretical understanding of the nature of neutrinos and may be evidence for the grand unification of electromagnetic, weak and strong interactions. It is also evidence for physics beyond the "standard model".

If ν_μ's oscillate into ν_τ's with the parameterization implied by the Super-Kamiokande measurements and the solar neutrino observations, (Ganzalez-Garcia and Nir 2002) then the fluxes of these two neutrino flavors observed from astrophysical sources should be equal. This is because cosmic neutrinos arrive from such large distances that many oscillations are expected to occur during their journey, equalizing the fluxes in both flavor states. Otherwise, the fluxes of ν_τ's from such sources would be much less than those of ν_μ's because ν_μ's are produced abundantly in the decay of pions which are easily produced in cosmic sources, whereas ν_τ's are not.

Upward-moving atmospheric showers induced by $\sim$100 TeV and traced back to the direction of a cosmic source such as an AGN or a GRB at a distance of 1 Gpc would occur even if the difference of the squares of the oscillating mass states were small as $\sim 10^{-17}$ eV^2. Thus, the search for upward moving showers from cosmic ν_τ's, which can propagate thorugh the Earth through regeneration at energies above 10^{14} eV (Halzen and

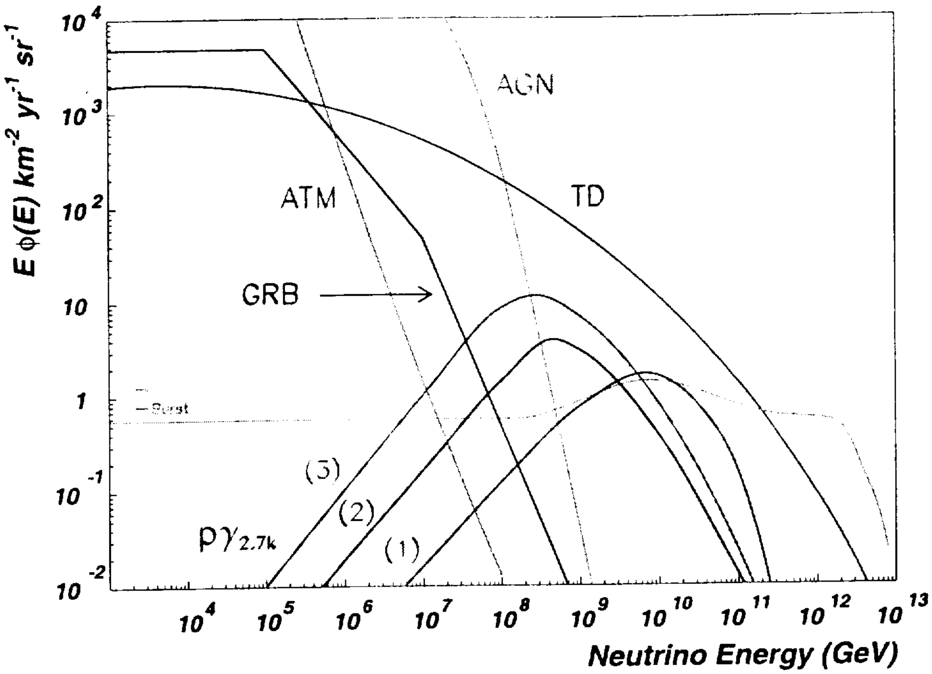

Figure 17. Some examples of neutrino flux predictions with $\nu_\mu \leftrightarrow \nu_\tau$ oscillations taken into account: Atmospheric and AGN fluxes (Stecker and Salamon 1996b); Photomeson production *via* $p\gamma_{2.7K}$ (as in Figure 16); Topological defects (Sigl, *et al.* 1998; $m_X = 10^{16}$ GeV supersymmetric model); Z_{Bursts} (Yoshida, Sigl, and Lee 1998, $m_\nu = 1$ eV, primary flux $\propto E^{-1}$); γ-ray bursts (Waxman and Bahcall 1997).

Saltzberg 1998; see section 5.2), provides a test for cosmic high energy ν_τ's from neutrino oscillations.

Another important signature of ultrahigh energy ν_τ's is the "double bang" which they would produce. The first shower is produced by the original interaction which creates a τ lepton and a hadronic shower. This is followed by the decay of the τ which produces the second shower bang (Learned and Pakvasa 1995). The two bangs are separated by a distance of $\sim 91.4\ \mu$m times the Lorentz factor of the τ.

4.7. NEUTRINO FLUX PREDICTIONS

Figure 17 illustrates some high energy neutrino flux predictions from various astrophysical sources discussed above as a function of neutrino energy. Note that the curves show the differential $\nu_\mu + \bar{\nu_\mu}$ flux multiplied by E_ν. In this figure, $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are assumed to reduce the cosmic high energy neutrino fluxes (including those shown in Figure 16) by a factor of 2.

In the energy range of 0.1 to 100 PeV, the AGN neutrino flux may dominate over other sources. However, neutrinos from individual γ-ray bursts may be observable and distinguishable *via* their directionality and short, intense time characteristics. The time-averaged background flux from all bursts is shown in the figure.

In the energy range $E \geq 1$ EeV, neutrinos are produced from photomeson interactions of ultrahigh enrgy cosmic rays with the 2.7 K background photons. The highest energy neutrinos ($E \geq 100$ EeV) are presumed to arise from more the speculative physics of topological defects and Z-bursts.

4.8. OBSERVATIONAL SIGNATURES AND RATES

4.8.1. *Signatures*

The proposed high energy neutrino sources also have different signatures in terms of other observables which include coincidences with other observations (GRB's), anisotropy (Z-burst's), and specific relations to the number of hadronic or photonic air showers also induced by the phenomena (topological defects, Z-burst's, and 2.7K photomeson neutrinos).

The distiguishing characteristics of astrophysical neutrino sources are summarized in the Table 1. In the table, the characteristic neutrino energy for photomeson processes is defined as $\sim 1.8 \times 10^{-2} M_p^2/\bar{\epsilon}$ where $\bar{\epsilon}$ is the mean energy of the photon field (Stecker 1979), except for the case of GRB neutrinos where the energy is boosted by a factor of Γ^2 where $\Gamma \sim 10^3$ is the bulk Lorentz factor of the GRB fireball (Waxman and Bahcall 1997).

The distribution of the atmospheric depth of neutrino interactions is approximately uniform due to the extremely long interaction path of neutrinos in the atmosphere. This offers a unique signature of neutrino-induced airshowers as a significant portion of the neutrino interactions will be deep in the atmosphere, i.e. near horizontal, and well separated from airshowers induced by hadrons and photons.

At ultrahigh energies, the cross sections for ν and $\bar{\nu}$ interactions with quarks become equal (Gandhi *et al.* 1998). The interactions produce an ultrahigh energy lepton which carries off $\sim 80\%$ of the incident neutrino energy. The remaining 20% is in the form of a hadronic cascade. Charged current neutrino interactions will, on average, yield an UHE charged lepton and a hadronic airshower. At these energies, electrons will generate electronic airshowers while μ's and τ's will produce airshowers with reduced particle densities and thus, reduced fluorescence signals. As discussed above, he ν_τ'-induced showers have a "double-bang" signature. For example, a 10 EeV, τ decays after traveling $\gamma c \tau = 500$ km, producing a second airshower which is very well separated from the first, hadronic airshower at the neutrino interaction point.

Test	GRB	AGN	TD	Z-Burst	$p\gamma_{2.7K}$
Coincidence with a GRB	X	-	-	-	-
$(N_\nu/N_p) \gg 1$	-	-	X	X	-
$(N_\gamma/N_p) \gg 1$	-	-	X	X	-
Anisotropy	-	-	-	X	-
Characterisitic Energy	10^{16} eV	10^{14} eV	10^{21} eV	$\frac{10^{20}\ \mathrm{eV}}{m_\nu\ (\mathrm{eV})}$	10^{19} eV
Multiple Events	X	X	-	X	-

TABLE 1. Distinguishing characteristics of the different sources of ultra-high energy neutrinos (revised from Cline and Stecker 2000.)

5. Present and Future Detectors

Of the ground-based ultrahigh energy arrays, the *AGASA* array of particle detectors in Japan is continuing to obtain data on ultrahigh energy cosmic ray-induced air showers. Its aperture is 200 km^{2}sr. The *HiRes* array is an extension of the Fly's Eye which pioneered the technique of measuring the atmospheric fluorescence light in the near UV (300 - 400 nm range). This light is isotropically emitted by nitrogen molecules that are excited by the charged shower secondaries at the rate of $\sim$4 photons per meter per particle. The estimated aperture of the *HiRes* monocular detector is $\sim$1000 km^{2}sr at 100 EeV after inclusion of a 10% duty cycle (Sokolsky 1998).

The southern hemisphere *Auger* array is expected to be on line in the near future. This will be a hybrid array which will consist of 1600 particle detector elements similar to those at Havera Park and three or four flourescence detectors (Zas 2001). Its expected aperture will be 7000 km^{2}sr for the ground array above 10 EeV and $\sim$ 10% of this number for the hybrid array.

The next big step will be to orbit a system of space-based detectors which will look down on the Earth's atmosphere to detect the trails of nitrogen flourescence light made by giant extensive air showers. The Orbiting Wide-angle Light collectors (*OWL*) mission is being proposed to study such showers from satellite-based platforms in low Earth orbit (600 - 1200 km). *OWL* would observe extended air showers from space via the air fluorescence technique, thus determining the composition, energy, and arrival angle distributions of the primary particles in order to deduce their origin. Operating from space with a wide field-of-view instrument dramatically increases the observed target volume, and consequently the detected air shower event rate, in comparison to ground based experiments. The *OWL* baseline configuration will yield event rates that are more than two orders of magnitude larger than currently operating ground-based experiments. The estimated aperture for a two-satellite system is 2.5×10^5 km^{2}sr above a few tens of EeV after assuming a 10% duty cycle.

OWL will be capable of making accurate measurements of giant air shower events with high statistics. It may be able to detect $\mathcal{O}(1000)$ giant air showers per year with $E \geq 100$ EeV (assuming an extrapolation of the cosmic ray spectrum based upon the AGASA data). The European Space Agency is now studying the feasibility of placing such a light collecting detector on the International Space Station in order to develop the required technology to observe the flourescent trails of giant extensive air showers, and to serve as a pathfinder mission for a later free flyer. This experiment has been dubbed *EUSO* (Extreme Universe Space Observatory; see paper of Livio Scarsi, these proceedings.) Owing to the orbit parameters and constraints of the International Space Station, the effective aperture for EUSO will not be as large as that of a free flyer mission. A recent compendium of papers on observing giant air showers from space may be found in Krizmanic, Ormes and Streitmatter (1998).

5.1. DETECTION OF NEUTRINO EVENTS FROM SPACE

The proposed Orbiting Wide-angle Light collectors satellite mission, *OWL*, would have the unmatched capacity to map the arrival directions of cosmic rays over the entire sky and thus to reveal the locations of strong nearby sources and large-scale anisotropies, this owing to the magnetic stiffness of charged particles of such high energy. Thus, with such a detector system, one can investigate energy spectra of any detected sources and also time correlations with high energy ν's and γ-rays.

Preliminary Monte Carlo simulations for an *OWL* space-based detector (J. Krismanic, private communication) have indicated that charged current electron neutrino interactions can be identified with a neutrino aperture of

20 km^2-ster at a threshold energy of 30 EeV and the aperture size grows with energy $\propto E_\nu^{0.363}$ with the increase in neutrino cross section (Gandhi *et al.* 1998). Event rates can be obtained by convolving this neutrino aperture with neutrino flux predictions and integrating. Note that the neutrino interaction cross section is included in the definition of neutrino aperture. Assuming a 10% duty cycle of the experiment, The ν_e event rates from several possible UHE neutrino sources as shown in Figure 17 are found to be as follows: neutrinos from the interaction of UHE protons with the microwave background ($p\gamma_{2.7K}$)—-5 events per year; topological defects—-10 events per year; neutrinos from Z-bursts—-9 events per year.

5.2. UPWARD ČERENKOV EVENTS FROM COSMIC TAU-NEUTRINOS

The ensemble of charged particles in an airshower will produce a large photon signal from Čerenkov radiation which is strongly peaked in the forward direction and which is much stronger than the signal due to air fluorescence at a given energy. This translates into a much reduced energy threshold for observing airshowers *via* Čerenkov radiation. As this signal is highly directional, an orbitting instrument will only observe those events where the airshower is moving towards the experiment with the instrument located in the field of the narrow, Čerenkov cone. Thus, it is possible ot observe upward moving events from ν_τ's which have propagated through the Earth (see section 4.5.)

Virtually all particles, including neutrinos with $E \geq 40$ TeV, are attenuated by the Earth. However, ν_τ's will regenerate themselves, albeit at a lower energy, due to the fact that both charged and neutral current interactions will have a ν_τ in the eventual, final state (Halzen and Saltzberg 1998). The ν_τ interactions produce a leading high-energy τ which then decays to produce another ν_τ.

For ν_τ interactions in the Earth's crust, the τ's will have a flight path of length $\gamma c\tau$ ($\approx$ 50 m at 1 PeV before they decay. Those events which occur at a depth less than $\gamma c\tau$ will produce a τ coming out of the Earth and generating an airshower. For a target area of 10^6 km^2, this yields a target mass of $10^8(E_\nu(\mathrm{GeV})$ metric tons, *e.g.,* 10^{14} metric tons at an energy of 1 PeV for the Earth as an effective detector mass.

Preliminary investigations of the response of an *OWL* space-based detector have indicated that the experiment would have a threshold energy of about 0.1 PeV to upward, Cherenkov airshowers. Assuming that the Super-Kamiokande atmospheric neutrino results are due to $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, the predicted AGN ν_μ flux (Stecker and Salamon 1996b) indicates that *OWL* could observe several hundred ν_τ events per year. Thus *OWL* would be able measure the flux of putative AGN neutrinos and observe their oscillations into ν_τ's.

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